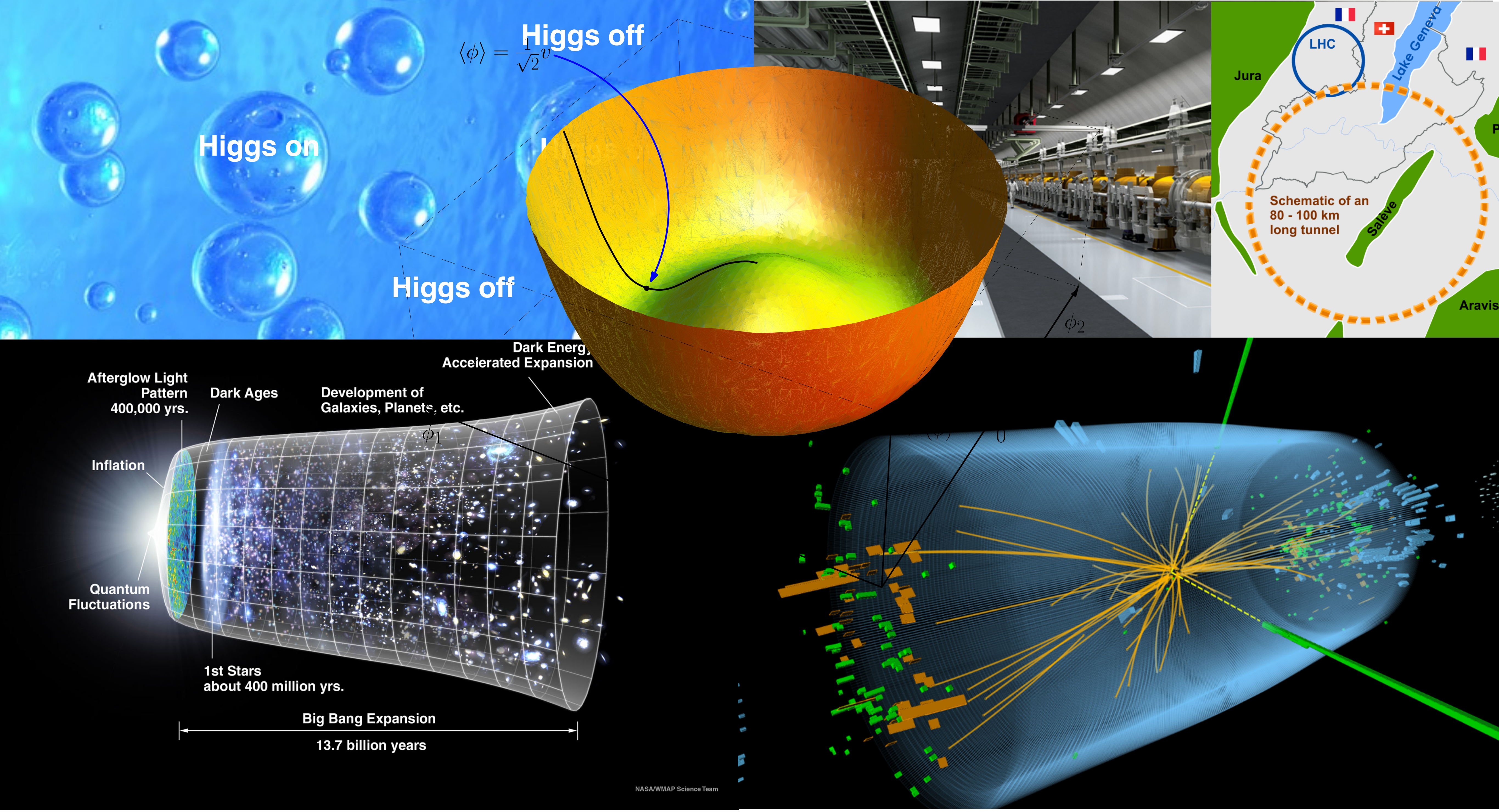

Higgs, flavour and ALPs: gaining a better understanding of our Universe

Georg Weiglein, DESY & UHH

DESY, 07 / 2024

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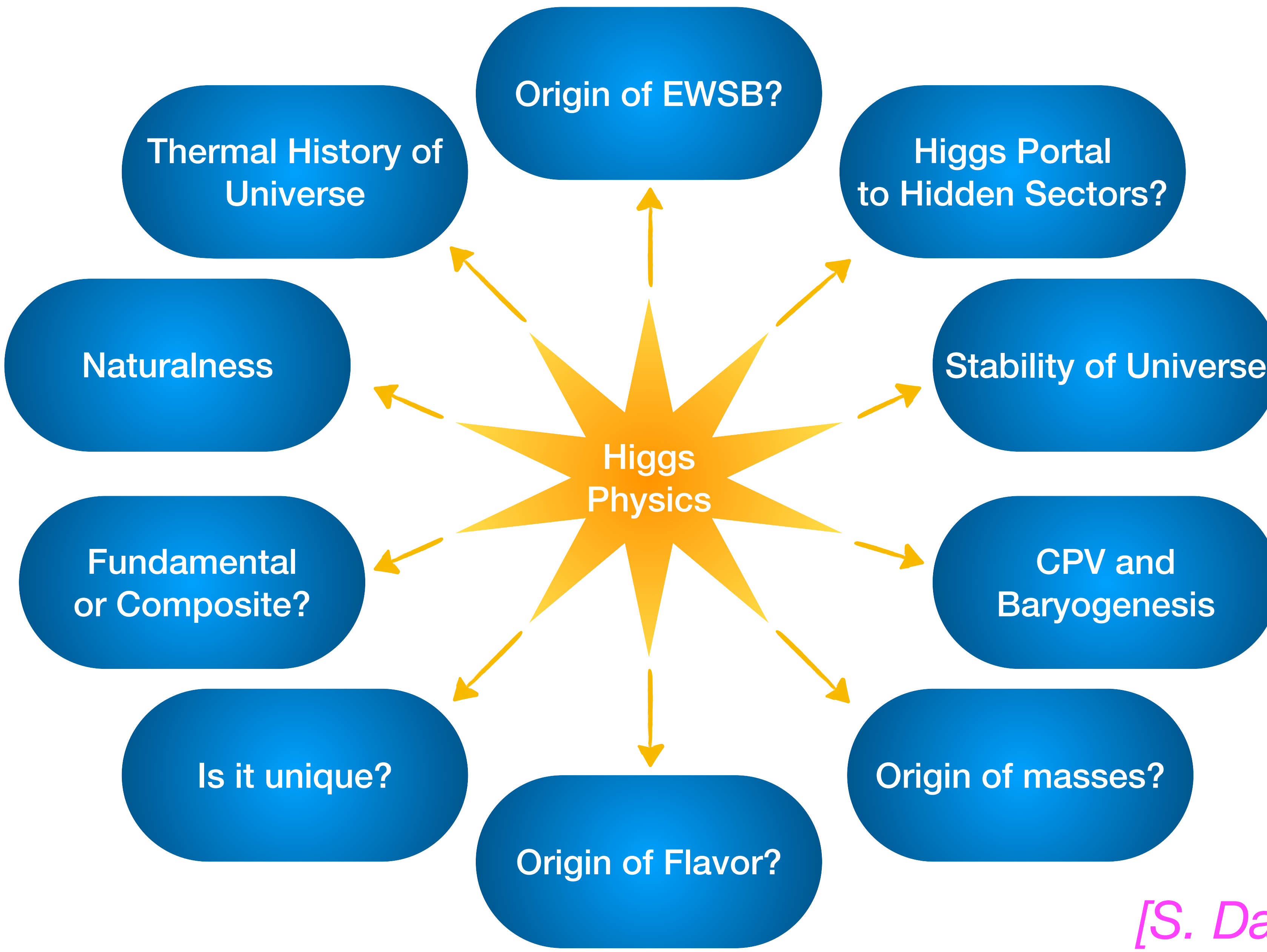
Introduction

Most of the open questions of particle physics are directly related to Higgs physics and in particular to the Higgs potential



[S. Dawson et al. '22]

Unsolved issues: Higgs / flavour, strong CP problem

[W. Altmannshofer ’24]

CC problem

Hierarchy problem

Vacuum stability?

Strong CP problem

$$\mathcal{L}_{\mathrm{SM}} \sim \Lambda^4 + \Lambda^2 H^2 + \lambda H^4$$

$$+ \bar{\Psi} \not{D} \Psi + (D_\mu H)^2 + (F_{\mu\nu})^2 + F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$+ Y H \bar{\Psi} \Psi + \frac{1}{\Lambda}(LH)^2 + \frac{1}{\Lambda^2}\sum_i \mathcal{O}_i^{\mathrm{dim6}} + \ldots$$

SM flavor puzzle

Neutrino masses

Flavorful new physics?

+ light new physics

Flavorful portals?

Flavour physics: basic open questions

- What is the origin of the observed flavour structure in the quark and in the lepton sector?

- Are there new sources for flavour and / or CP violation?
  CKM phase: only source of CP violation? Not compatible with the observed asymmetry between matter and anti-mattered in the Universe (see below)!

Current situation regarding ``flavour anomalies”: BSM physics or underestimated hadronic effects?

The QCD axion and axion-like particles (ALPs)

- Strong CP problem: no observation of CP violation in QCD although it would be allowed from first principles
- Solved by axions – BSM particles that exhibit U(1) shift symmetry
- In general: axion-like particles = particles with the same symmetry
  - Arise in many high-energy theories
  - Promising candidates for dark matter or dark matter mediators

[L. Jeppe '23]

$$\mathcal{L}_{QCD} \supset \theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}$$

CP-violating!
Obs.: $\theta < 10^{-10}$

Axion *a*: CP-odd scalar

$$\mathscr{L}_{aGG} = -\frac{\alpha_s}{8\pi}\left(\frac{a}{f_a} + \bar{\theta}\right) G^a_{\mu\nu} \widetilde{G}^{a\mu\nu}$$

$$\bar{\theta} = \theta_{\mathrm{QCD}} + N_f \theta_Y$$

a evolves towards the minimum of the QCD-induced potential

$$\Rightarrow \left(\frac{a}{f_a} + \bar{\theta}\right) \longrightarrow 0$$

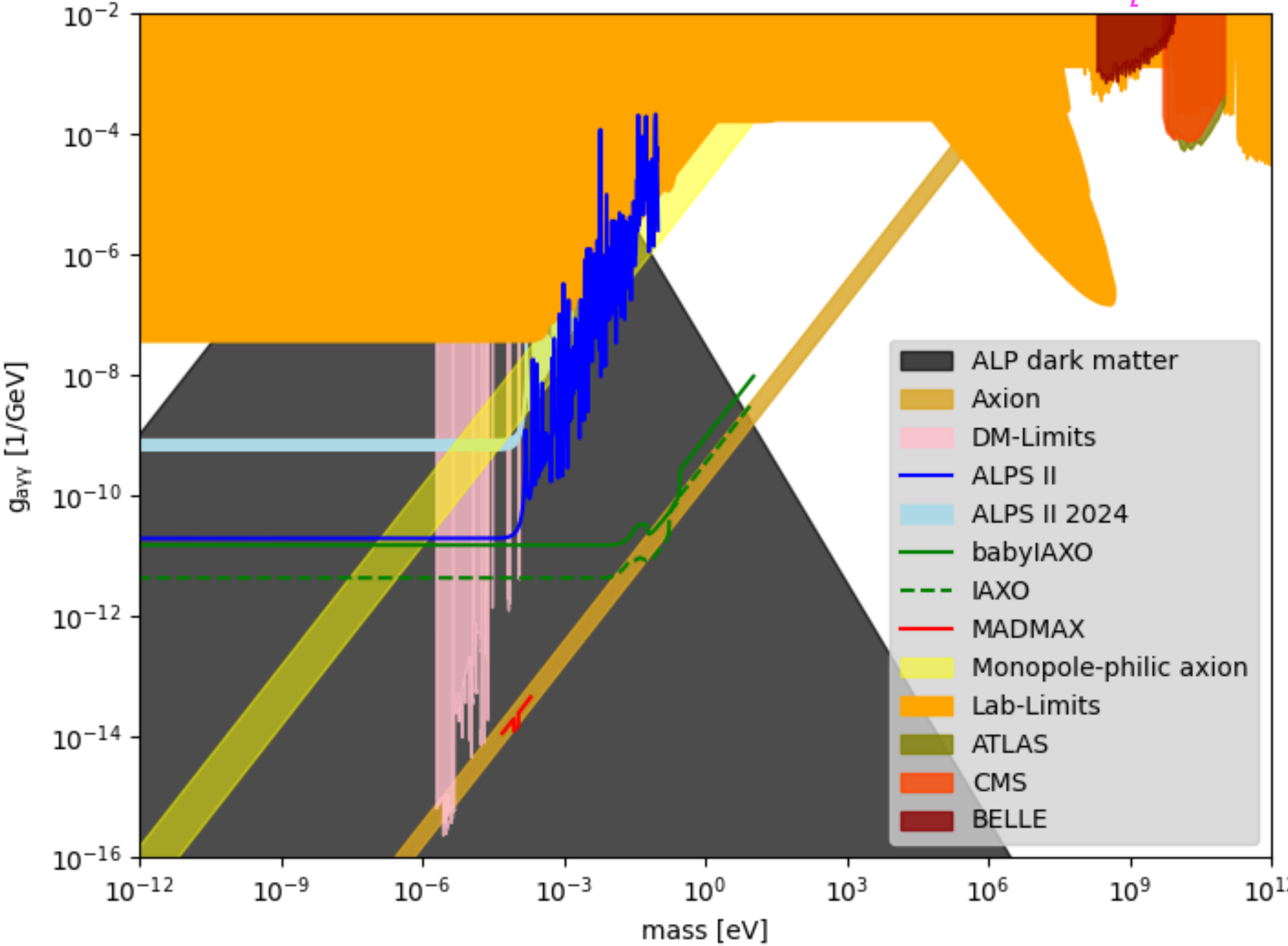
Effective ALP Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + \frac{m_a^2}{2} a^2 - \frac{a}{f_a} c_{\tilde{G}} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + i c_t \frac{a}{f_a} \left(\bar{q}\, Y_t \tilde{H}\, t_R + \mathrm{h.c.}\right)$$

ALP couplings

Existing and projected axion limits

[A. Lindner et al. '24]



QCD axion vs. axion-like particles (ALPs)

[R. Catena '24]

- One important constraint acting on the parameter space of axions is

$$m_a f_a \simeq m_\pi f_\pi$$

- Axion-like Particles, or ALPs, are characterised by their mass m_a being independent of f_a

- They are predicted to arise generically, in addition to the axion, in low-energy effective field theories emerging from string theory

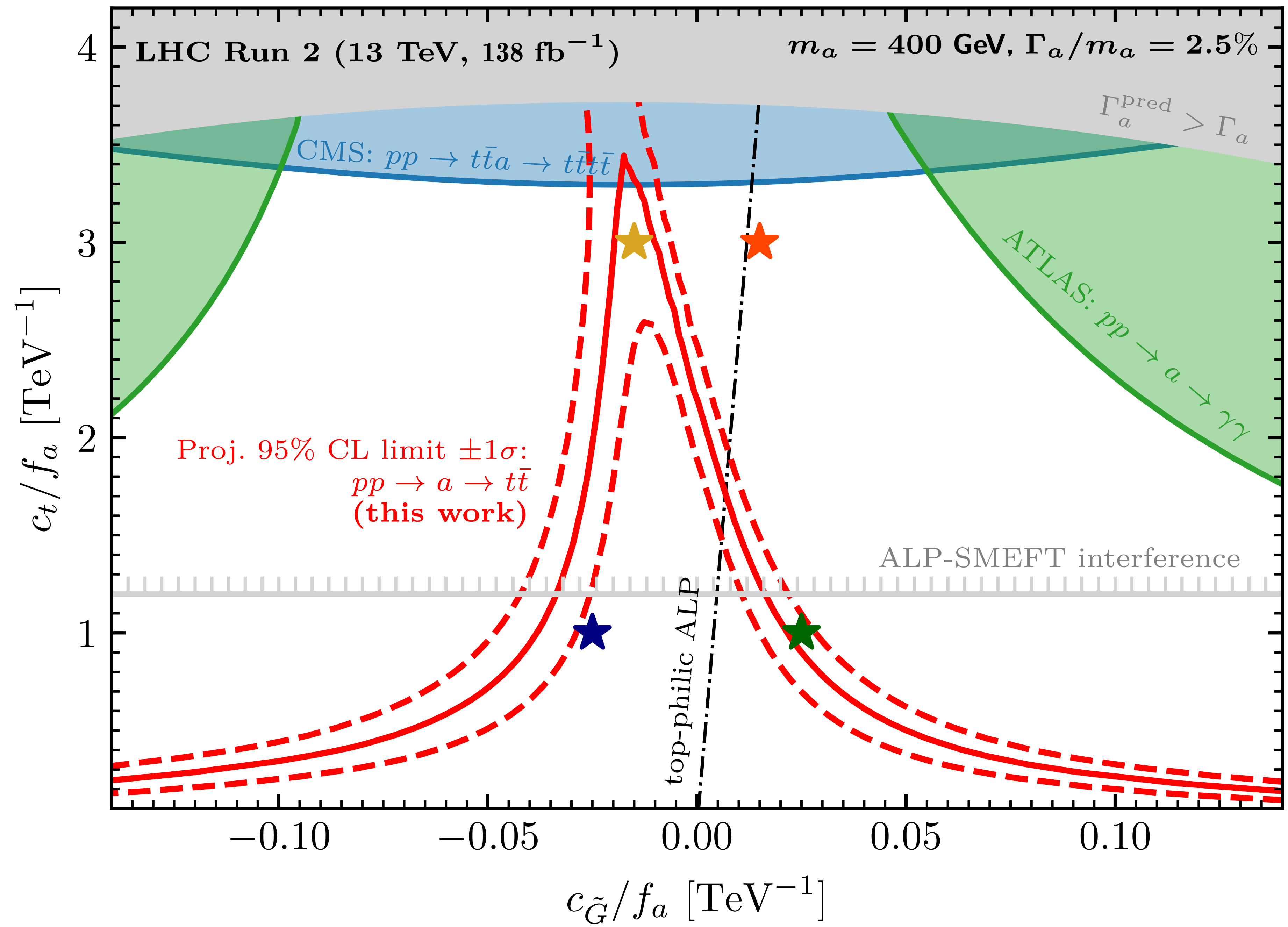
  E. Witten (1984)

- They are in general unrelated to QCD and do not provide a solution to the strong CP problem

- Multidimensional parameter space

Heavy ALP (not DM candidate) at the LHC: a → tt

[A. Anuar et al. '24]

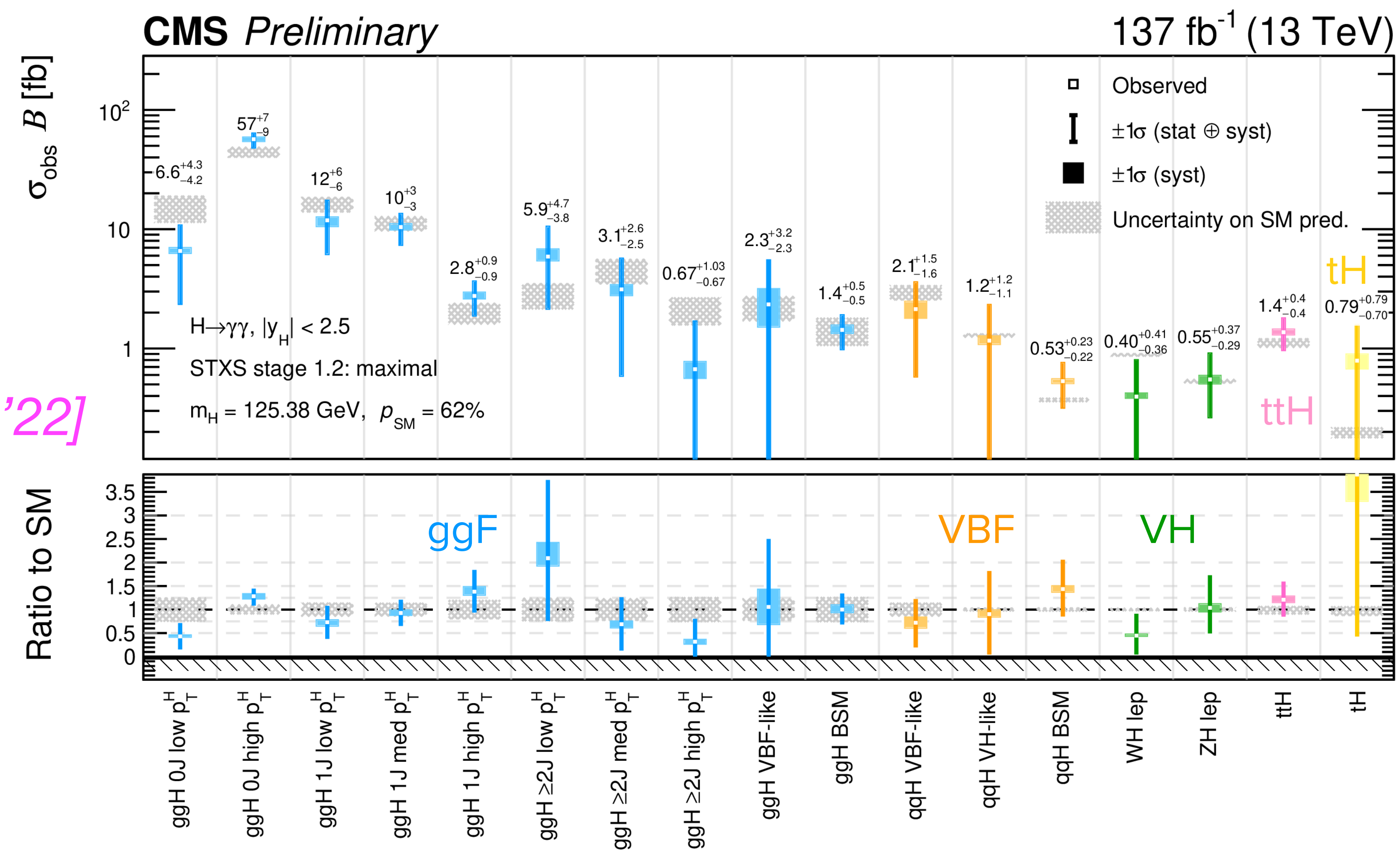


Direct search limits for di-top final state yield stringent constraints, comparable or stronger than indirect limits from ALP-SMEFT interference

Properties of the detected Higgs boson (h125)

The Standard Model of particle physics uses a "minimal" form of the Higgs potential with a single Higgs boson that is an elementary particle

h125: inclusive and differential rates



[CMS Collaboration '22]

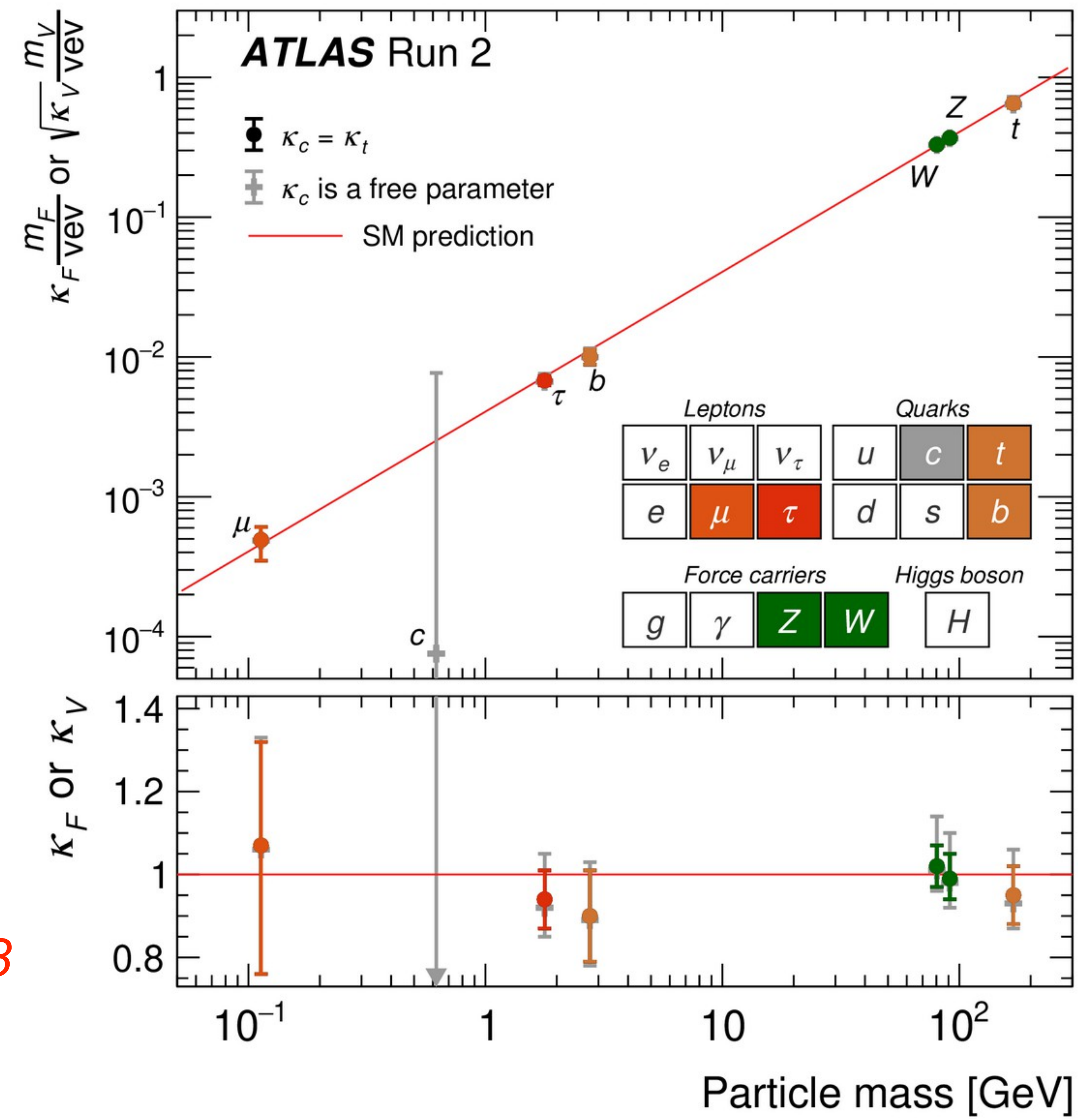
⇒SM-like properties

The LHC results on the discovered Higgs boson within the current uncertainties are compatible with the predictions of the Standard Model, but also with a wide variety of other possibilities, corresponding to very different underlying physics

Properties of the detected Higgs boson (h125)

Couplings of the detected Higgs boson to other particles:

[ATLAS Collaboration ’22]



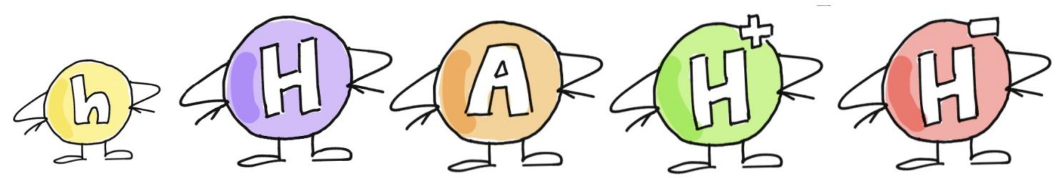
Nobel Prize 2013

⇒ Agrees with predictions of the Brout-Englert-Higgs (BEH) mechanism

Simple example of extended Higgs sector: 2HDM

Two Higgs doublet model (2HDM):

- **CP conserving** 2HDM with two complex doublets: $\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1+\rho_1+i\eta_1}{\sqrt{2}} \end{pmatrix}, \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2+\rho_2+i\eta_2}{\sqrt{2}} \end{pmatrix}$



[K. Radchenko '23]

- **Softly broken $\mathbb{Z}_2$ symmetry** ($\Phi_1 \to \Phi_1$; $\Phi_2 \to -\Phi_2$) entails 4 Yukawa types

- Potential: $$\boxed{\begin{aligned} V_{\text{2HDM}} = {} & m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \\ & \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}((\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2), \end{aligned}}$$

- Free parameters: $m_h,\ m_H,\ m_A,\ m_{H^\pm},\ m_{12}^2,\ \tan\beta,\ \cos(\beta-\alpha),\ v$

$$\boxed{\begin{aligned} &\tan\beta = v_2/v_1 \\ &v^2 = v_1^2 + v_2^2 \sim (246\ \text{GeV})^2 \end{aligned}}$$

In alignment limit, cos(β – α) = 0: h couplings are as in the SM at tree level

Masses of the BSM Higgs fields

$$m_A^2 = [m_{12}^2/(v_1 v_2) - 2\lambda_5]\,(v_1^2 + v_2^2) \qquad m_+^2 = [m_{12}^2/(v_1 v_2) - \lambda_4 - \lambda_5]\,(v_1^2 + v_2^2)$$

In general: BSM Higgs fields receive contributions from two sources:

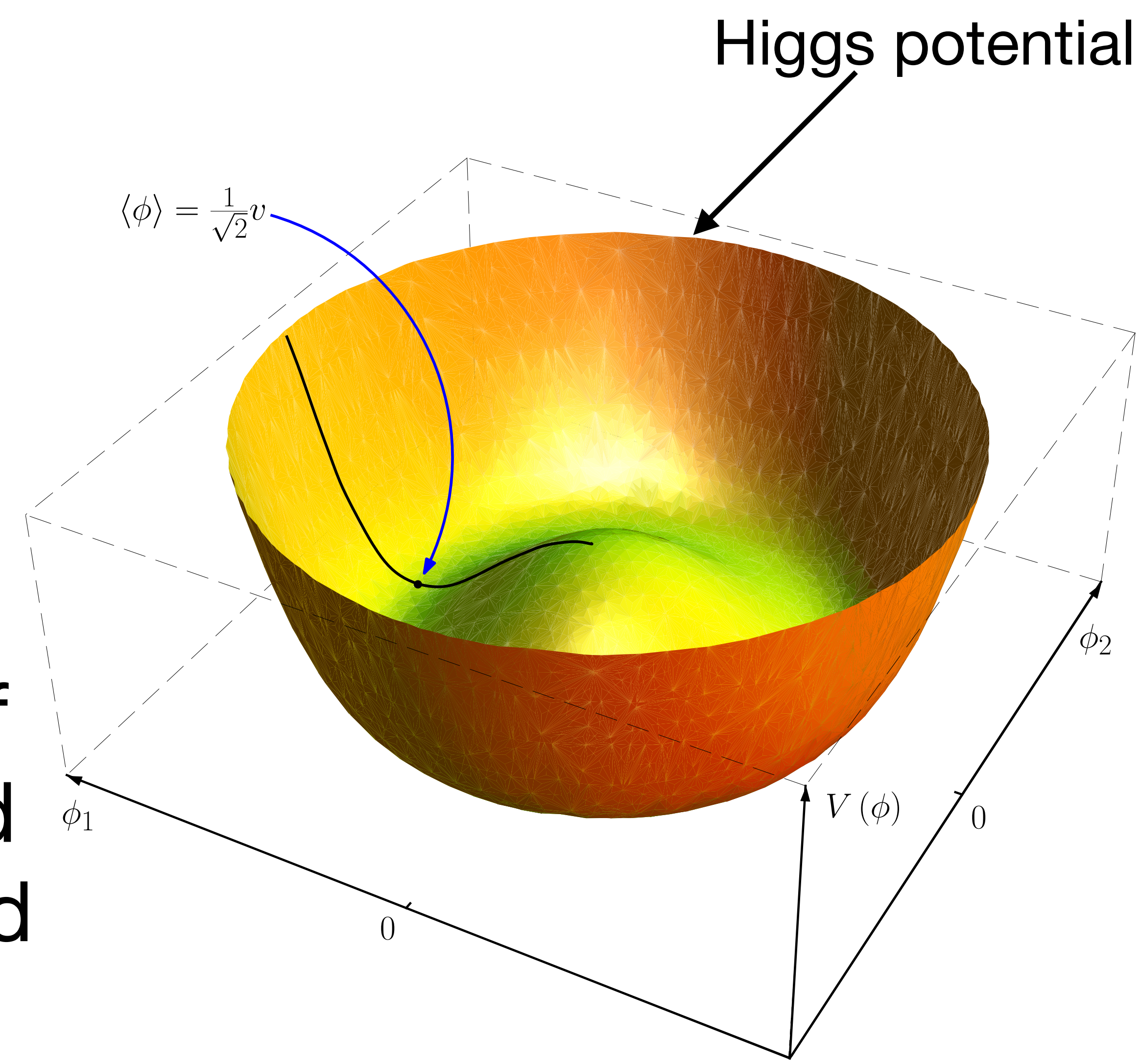
$$m_\Phi^2 = M^2 + \tilde{\lambda}_\Phi v^2\,, \quad \Phi \in \{H, A, H^\pm\}$$

where $M^2 = 2\, m_{12}{}^2/\sin(2\beta)$

Sizeable splitting between m_Φ and M induces large BSM contributions the the Higgs self-couplings (see below)

What is the underlying dynamics of electroweak symmetry breaking?

The vacuum structure is caused by the Higgs field through the Higgs potential. We lack a deeper understanding of this!



We do not know where the Higgs potential that causes the structure of the vacuum actually comes from and which form of the potential is realised in nature. Experimental input is needed to clarify this!

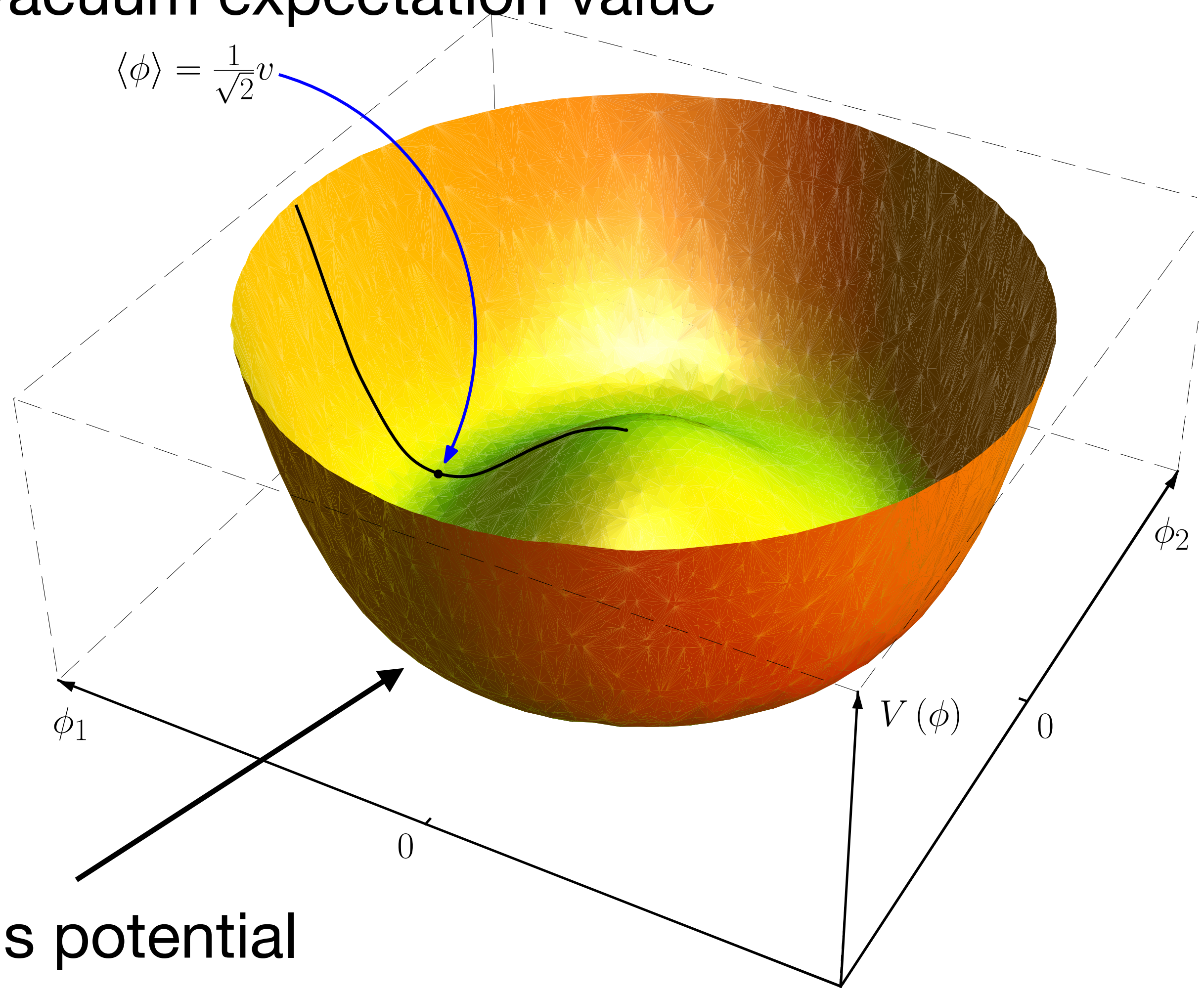
Single doublet or extended Higgs sector? (new symmetry?)

Fundamental scalar or compositeness? (new interaction?)

Higgs potential: the “holy grail” of particle physics

Crucial questions related to electroweak symmetry breaking: what is the form of the Higgs potential and how does it arise?

Vacuum expectation value



Higgs potential

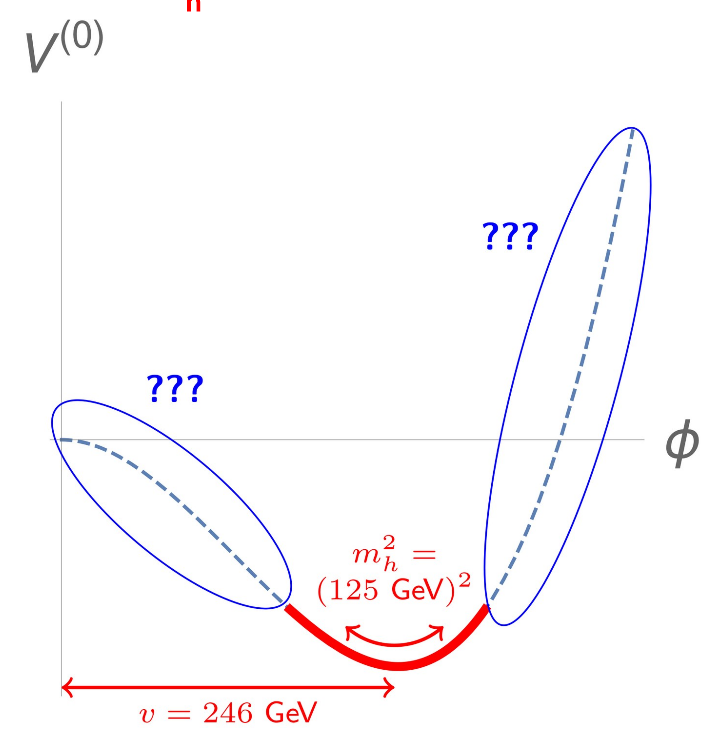
Only known so far:

→ the location of the EW minimum:

$v = 246$ GeV

→ the curvature of the potential around the EW minimum:

$m_h = 125$ GeV



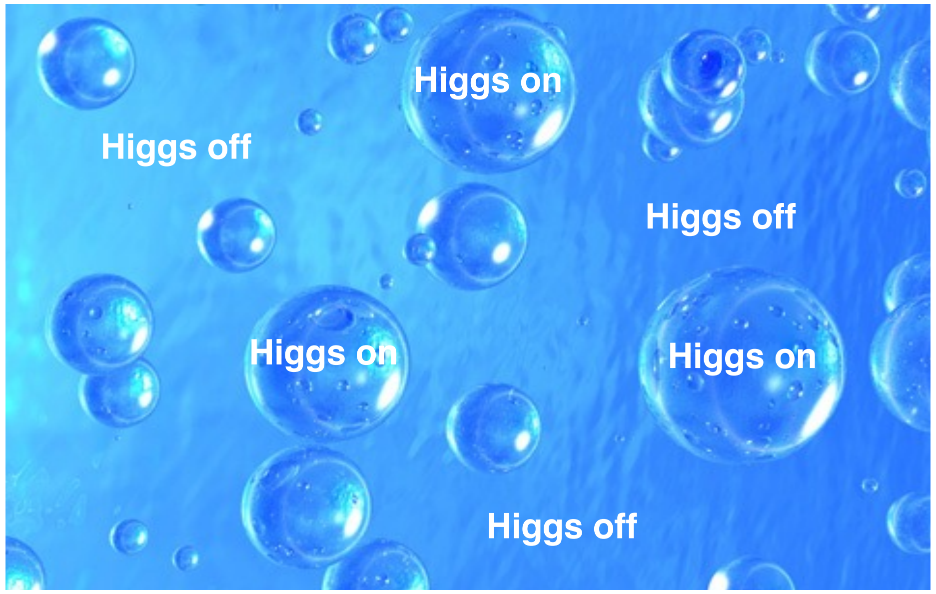
Information can be obtained from the trilinear and quartic Higgs self-couplings, which will be a main focus of the experimental and theoretical activities in particle physics during the coming years

The Higgs potential and the electroweak phase transition (EWPT)

[D. Gorbunov, V. Rubakov]

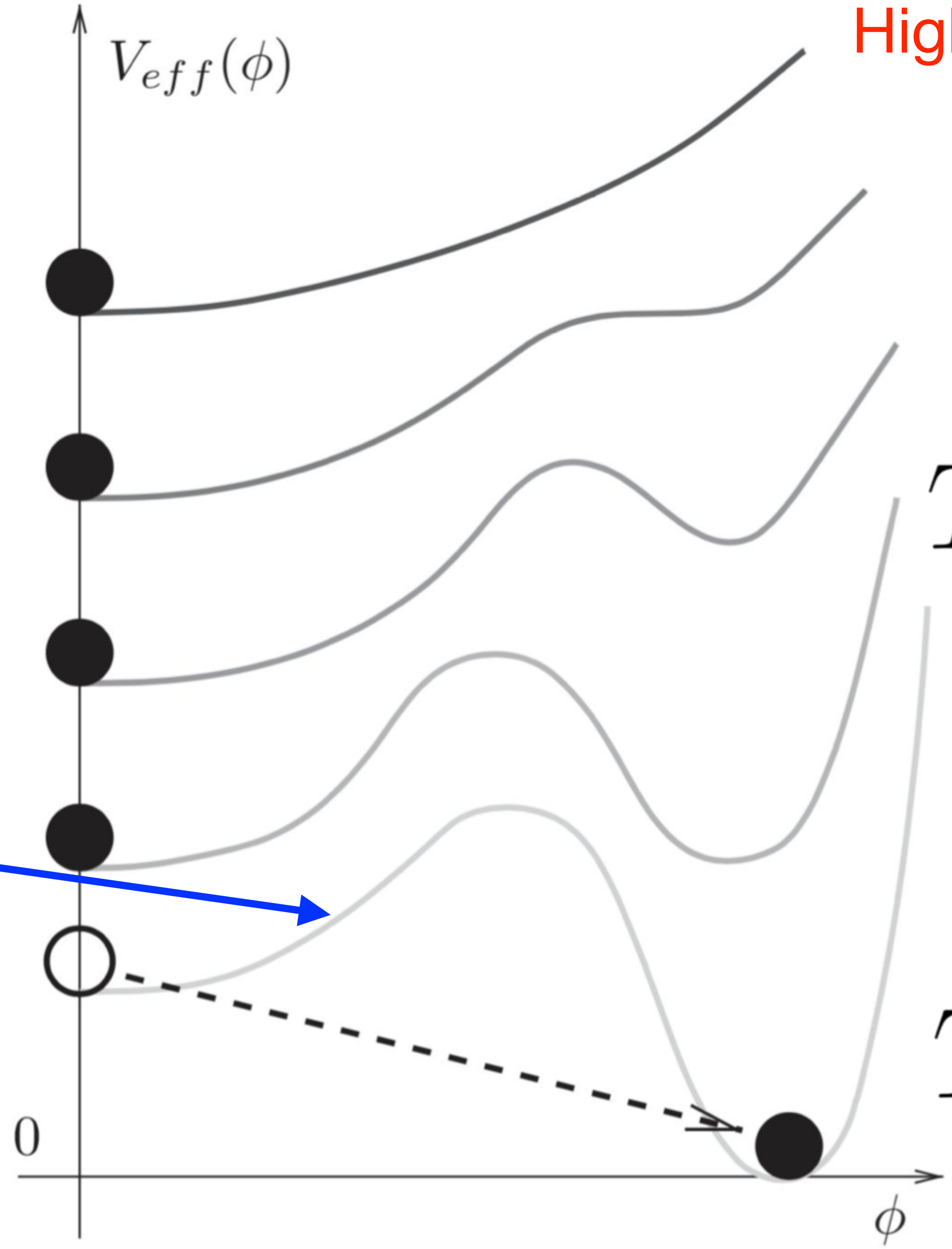
Temperature evolution of the Higgs potential in the early universe:

$$V(\phi, T) = V_0(\phi) + V^{loop}(\phi, T)$$



Potential barrier depends on trilinear Higgs coupling(s)

Baryogenesis: creation of the asymmetry between matter and antimatter in the universe requires strong first-order EWPT



High temperature

T_c Critical temperature (degenerate minima)

T_n Transition temperature (strong first-order EWPT)

Electroweak phase transition and baryon asymmetry

Observed Baryon Asymmetry of the Universe (BAU)

$$\eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} \simeq 6.1 \times 10^{-10}$$ [Planck ‘18]

n_b: baryon no. density
$n_{\bar{b}}$: antibaryon no. density
n_γ: photon no. density

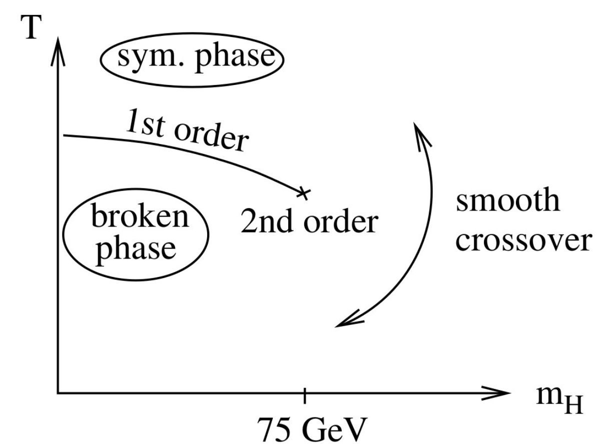
[J. M. No ’23]

Sakharov Conditions

(*for dynamical generation of baryon asymmetry*)

- B Violation
- C/CP Violation ✘ not enough in SM
- Departure from Thermal Equilibrium

SM phase diagram

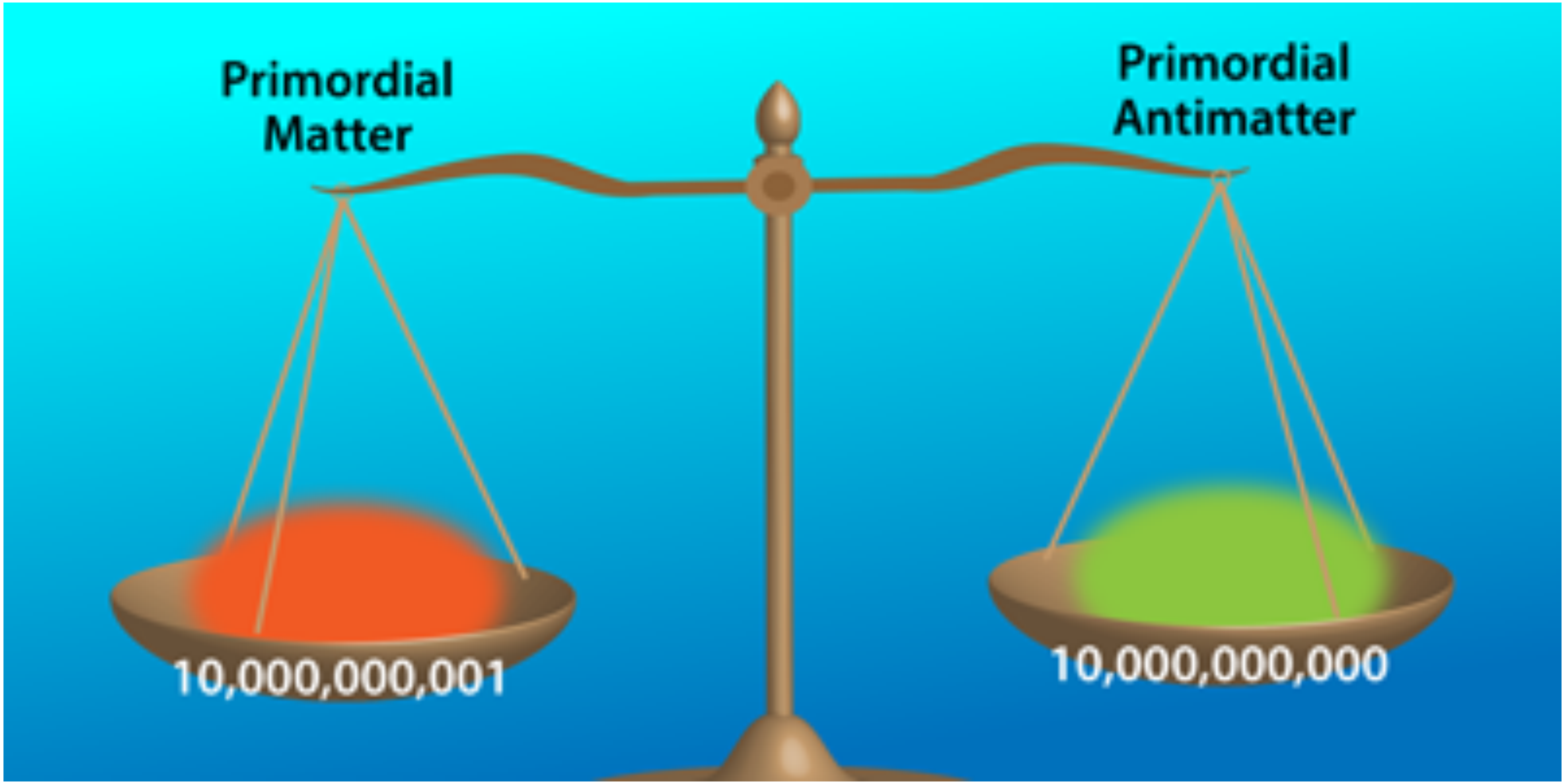


SM CP Violation insufficient by ~ 10 orders of magnitude

via 3-family fermion mixing
(CKM matrix)

Sakharov conditions:
- baryon (or lepton) number violation starting from symmetric state
- treat baryons and anti-baryons differently (to remove anti-matter)
- suppress inverse processes

Asymmetry between matter and anti-matter



The created little excess of matter over anti-matter resulted in the matter dominance that is observed today

Electroweak phase transition and baryon asymmetry

Sakharov conditions are necessary but not sufficient to produce the observed baryon asymmetry

Does not work in the SM: BSM physics needed

Exciting option: generate the baryon asymmetry during the electroweak phase transition (electroweak baryogenesis)

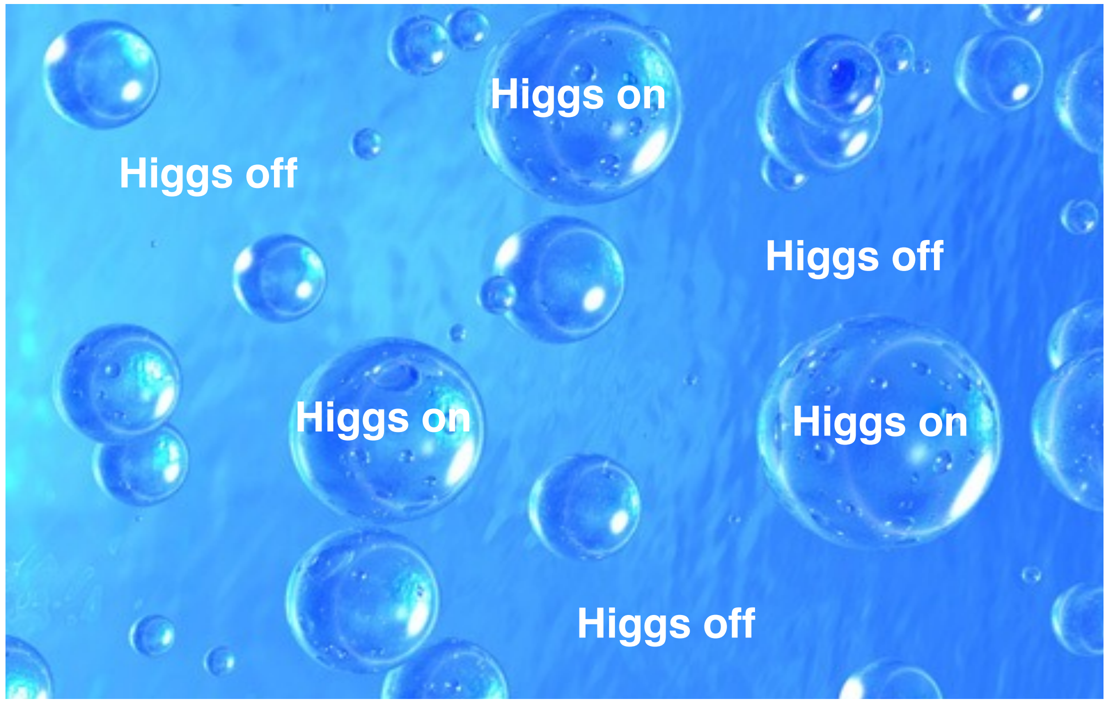
In the SM: baryon number conserved at classical level but violated at the quantum level (related to the axial anomaly)

Non-perturbative ``sphaleron” processes violate both baryon and lepton number (i.e., violate B+L), but preserve B−L

Baryon generation at the electroweak phase transition

Start from B=L at $T > T_C$

In a first-order EW phase transition the Universe tunnels from the phase with vanishing vacuum expectation value to the phase with non-vanishing vev via bubble nucleation



Bubbles expand near the speed of light; processes near the wall are highly out of thermal equilibrium

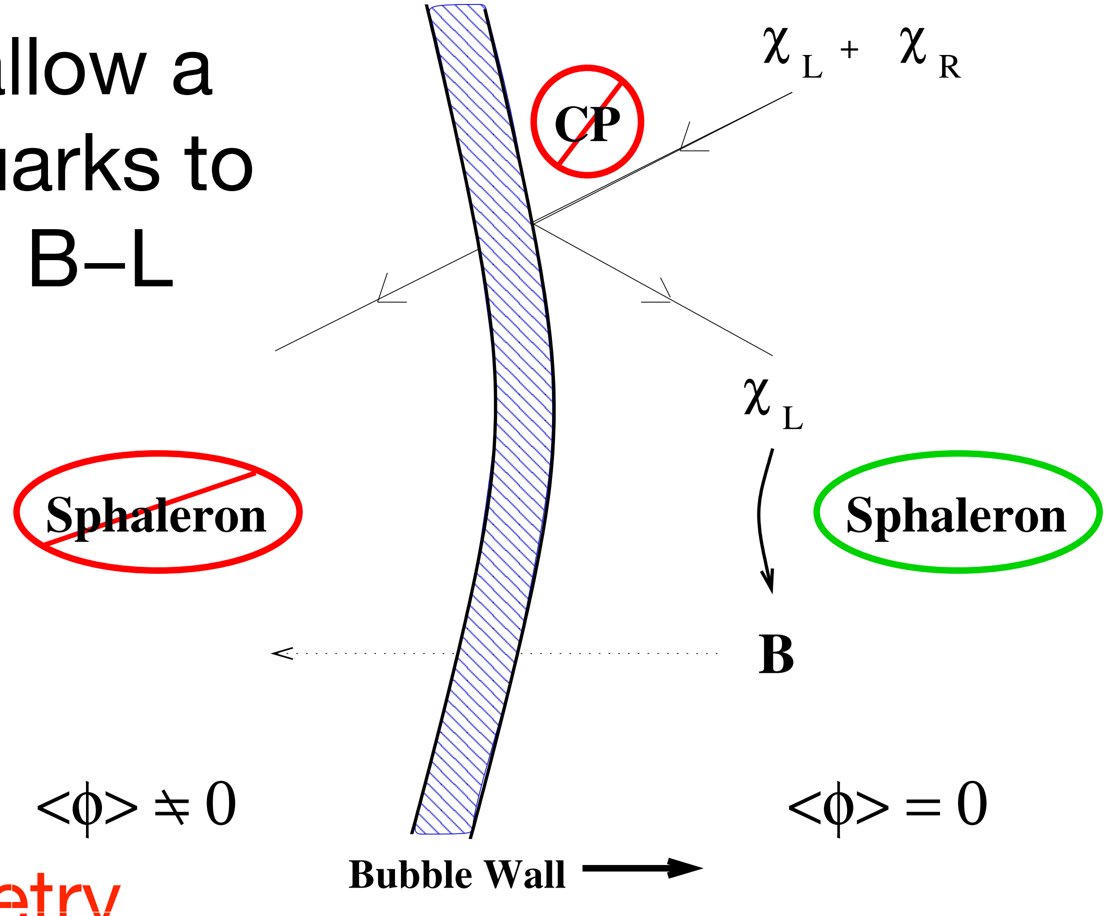
Baryon generation at the electroweak phase transition

Start from B=L at T > T_C

Particles flow into the expanding bubble wall, CP violation implies that the wall exerts different forces on particles and anti-particles
⇒ Creation of chiral asymmetry

[D.E. Morrissey, M.J. Ramsey-Musolf ’12]

Outside the bubble, EW sphalerons allow a fraction of the chiral asymmetry of quarks to be shared with leptons (B+L violated, B−L preserved)



⇒ Creation of net baryon asymmetry

Strong first-order EWPT needed to prevent the “washout” of the asymmetry

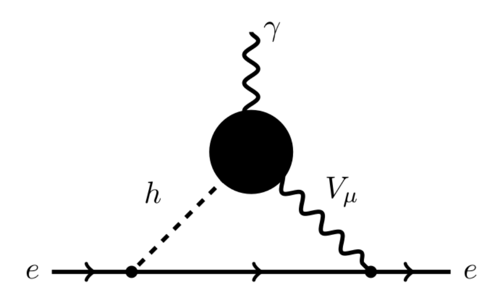
EWPT: are there additional sources for CP violation in the Higgs sector?

Baryogenesis: creation of the asymmetry between matter and anti-matter in the universe requires a strong first-order electroweak phase transition (EWPT)

First-order EWPT does not work in the SM
The amount of CP violation in the SM (induced by the CKM phase) is not sufficient to explain the observed asymmetry between matter and anti-matter in the universe

First-order EWPT can be realised in extended Higgs sectors could give rise to detectable gravitational wave signal

⇒ Search for additional sources of CP violation

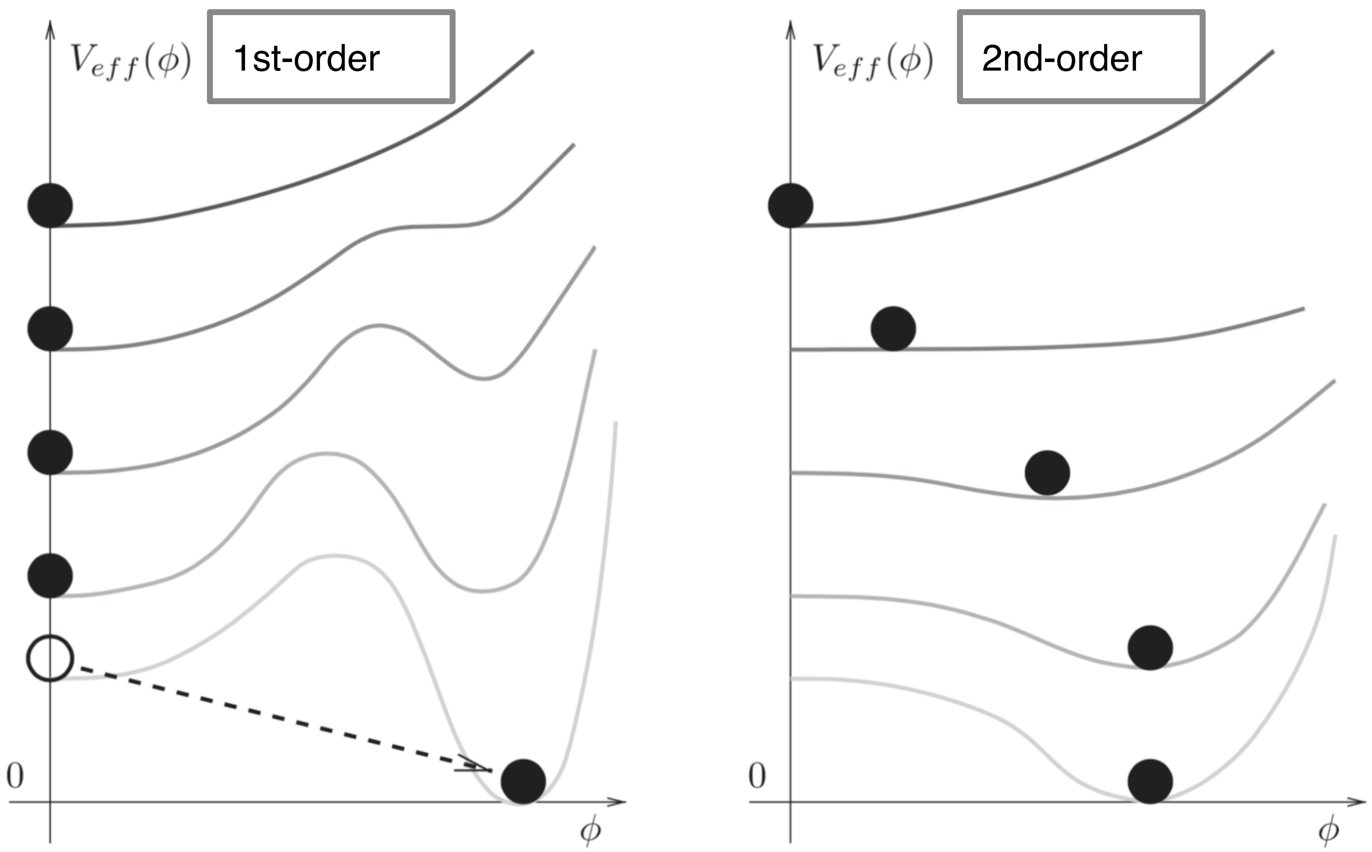


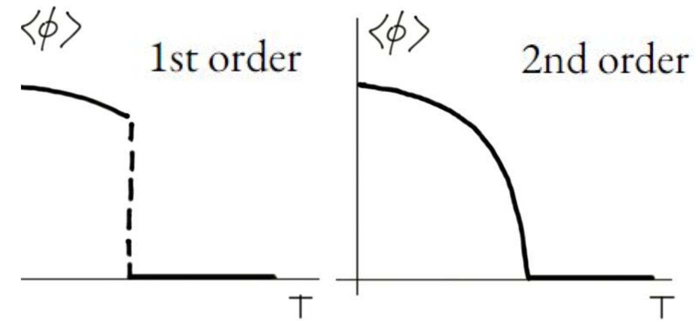
Two-loop "Barr-Zee" electron EDM contribution

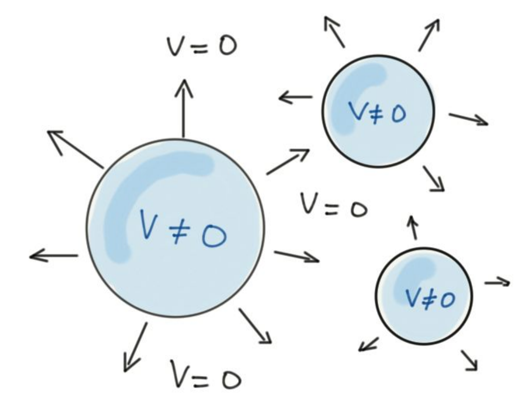
But: strong experimental constraints from limits on electric dipole moments (EDMs)

First-order vs. second order EWPT

[D. Gorbunov, V. Rubakov]





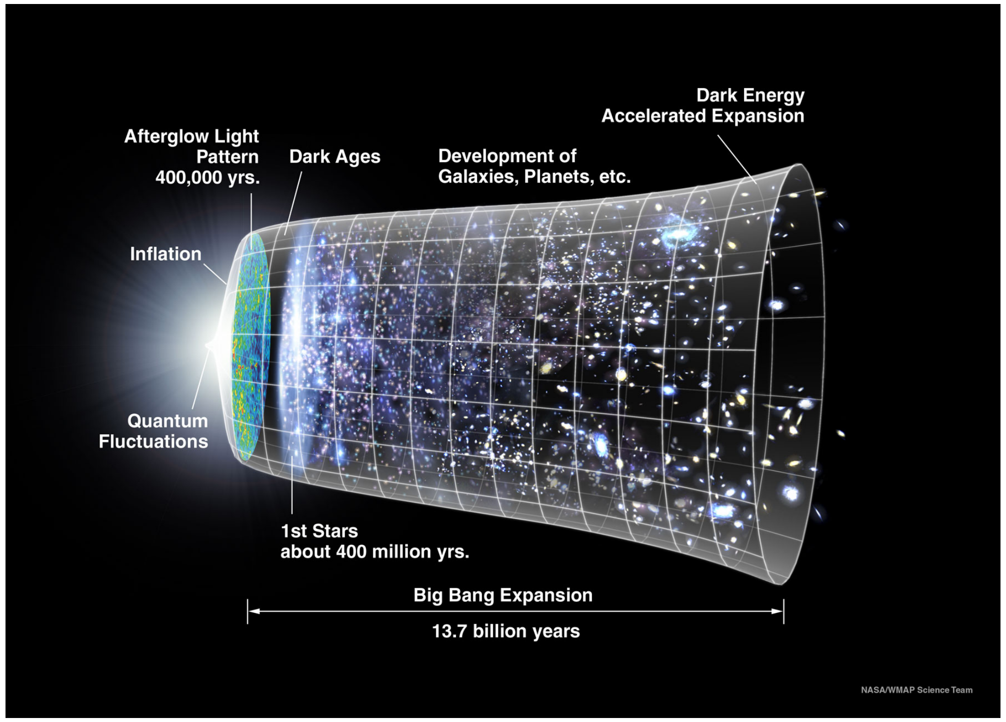


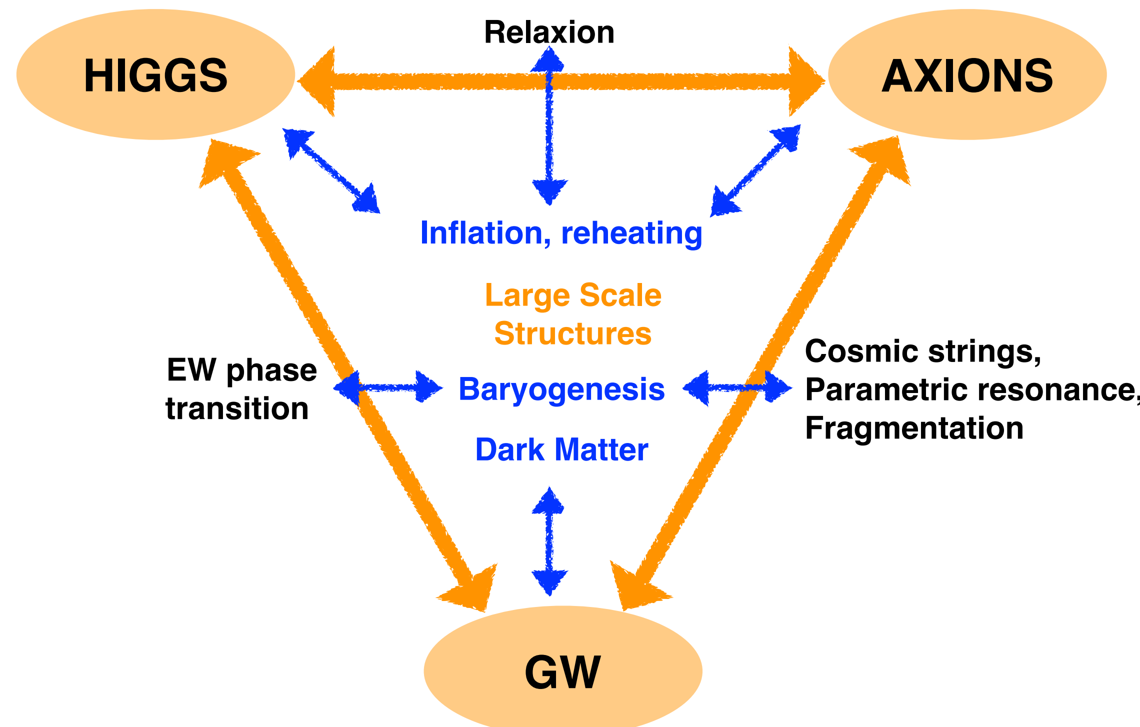
[K. Radchenko '23]

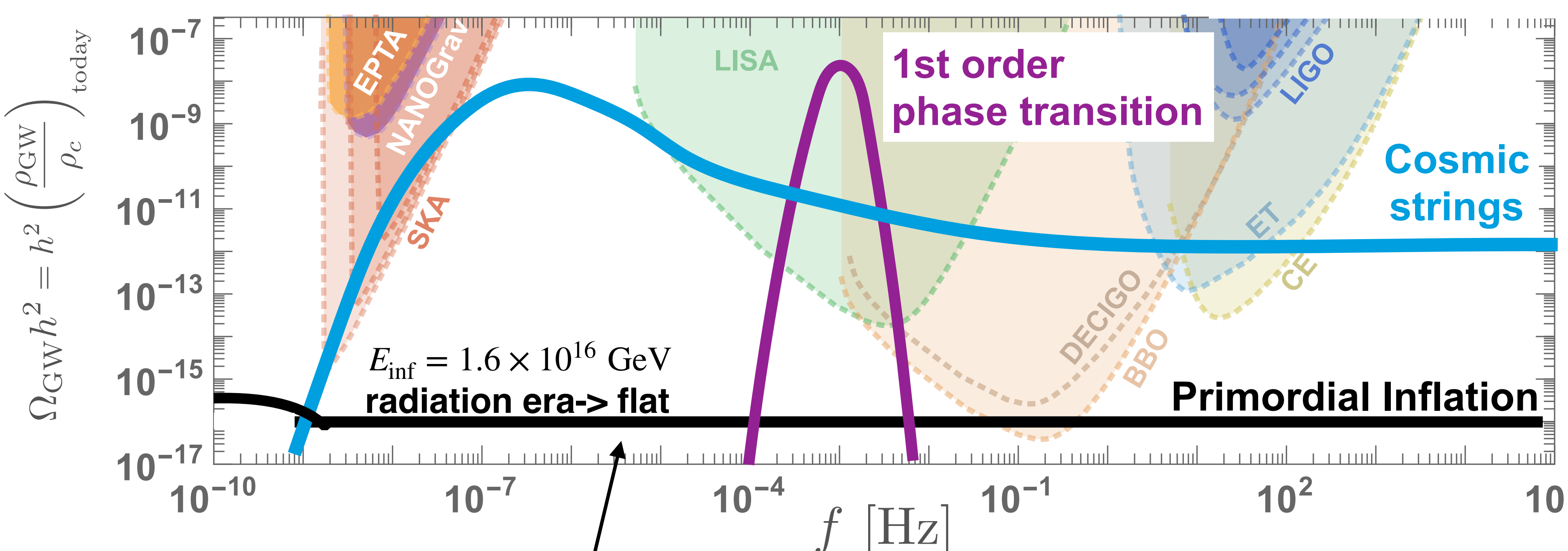
Potential barrier needed for first-order EWPT, depends on trilinear Higgs coupling(s)

Deviation of trilinear Higgs coupling from SM value is a typical feature of a strong first-order EWPT

Gravitational waves as a probe of the early universe

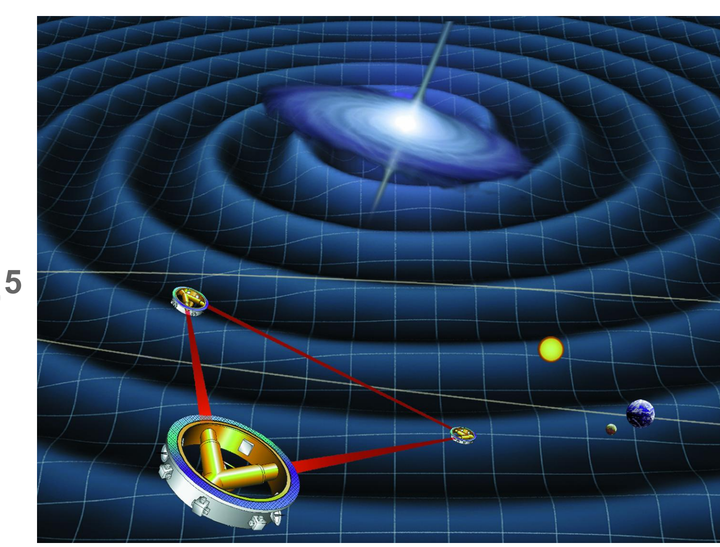




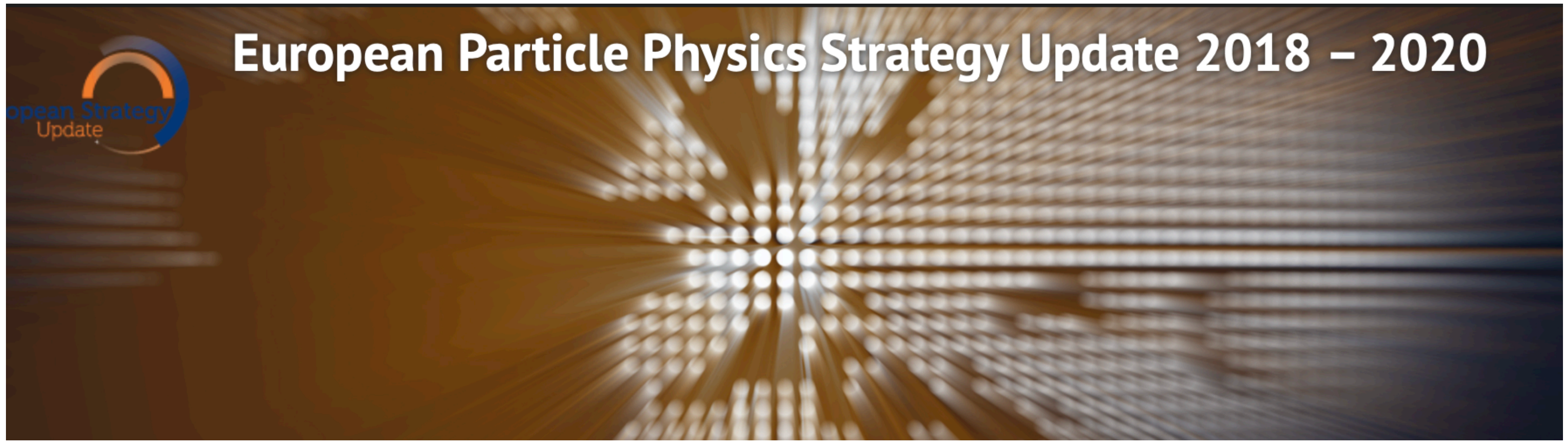


Irreducible GW background from amplification of initial quantum fluctuations of the gravitational field during inflation

LISA:



Latest update of European Strategy for Particle Physics



Future Projects:

3. High-priority future initiatives

a) An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

- *the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;*
- *Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.*

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

e+e− Higgs factories

Linear

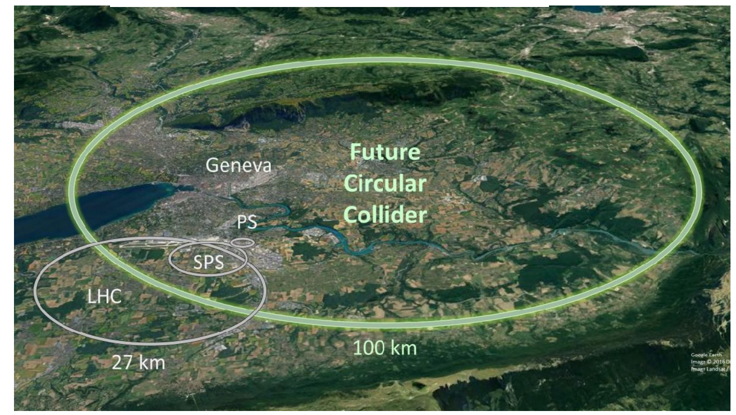
International **L**inear **C**ollider

ILC
Japan

Circular

FCC-ee
CERN

Future **C**ircular **C**ollider

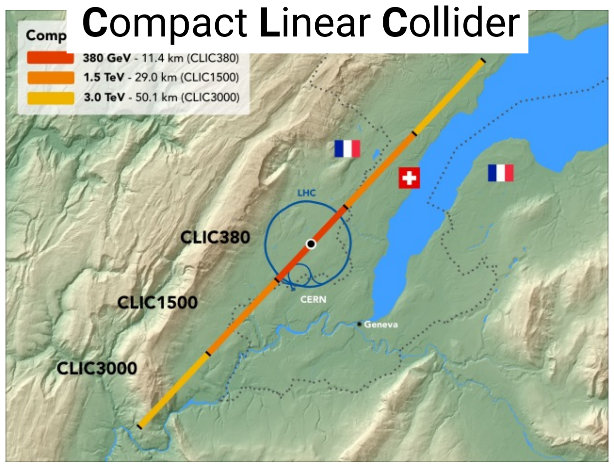


High-level differences:

- Energy reach
- Luminosity

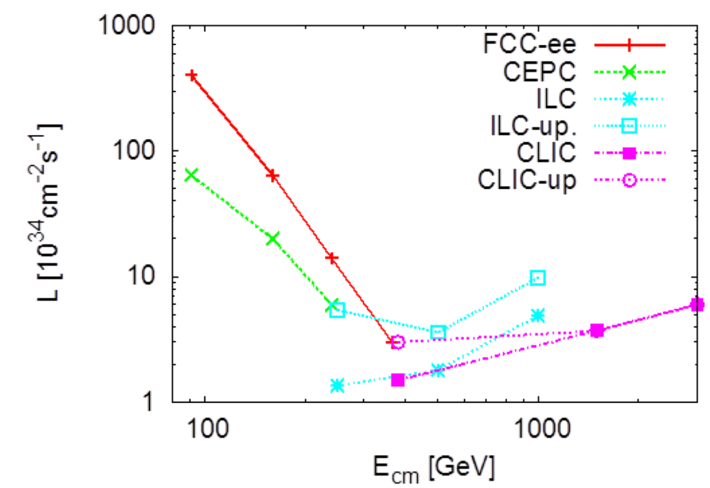
CLIC
CERN

Compact **L**inear **C**ollider

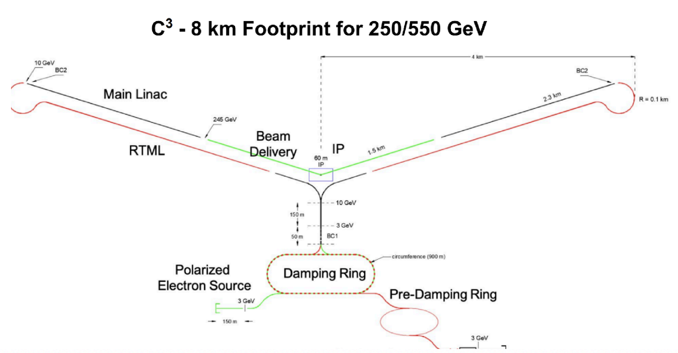


CEPC
China

Circular **E**lectron **P**ositron **C**ollider



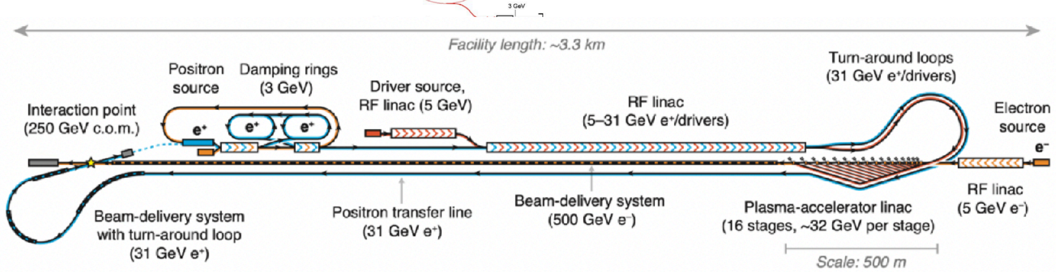
CCC



- 250 GeV — *ZH* threshold
- 350 GeV — *tt* threshold
- 550 GeV — *HHH* coupling
- ca. 1.5 TeV technology limit

- Based on superconducting RF (liquid nitrogen)
- Proposed at SLAC; very compact machine

HALHF

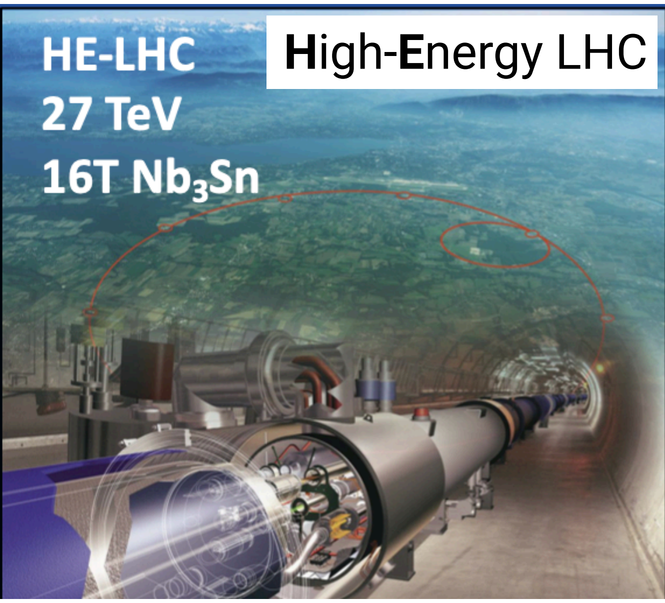


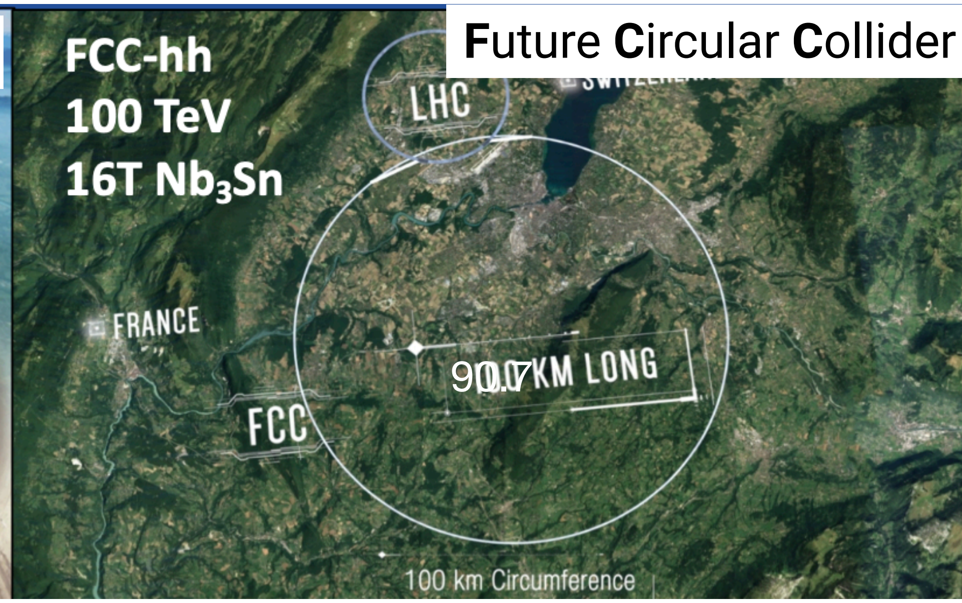
Source: **Foster, D'Arcy & Lindstrøm**, preprint at arXiv:2303.10150 (2023)

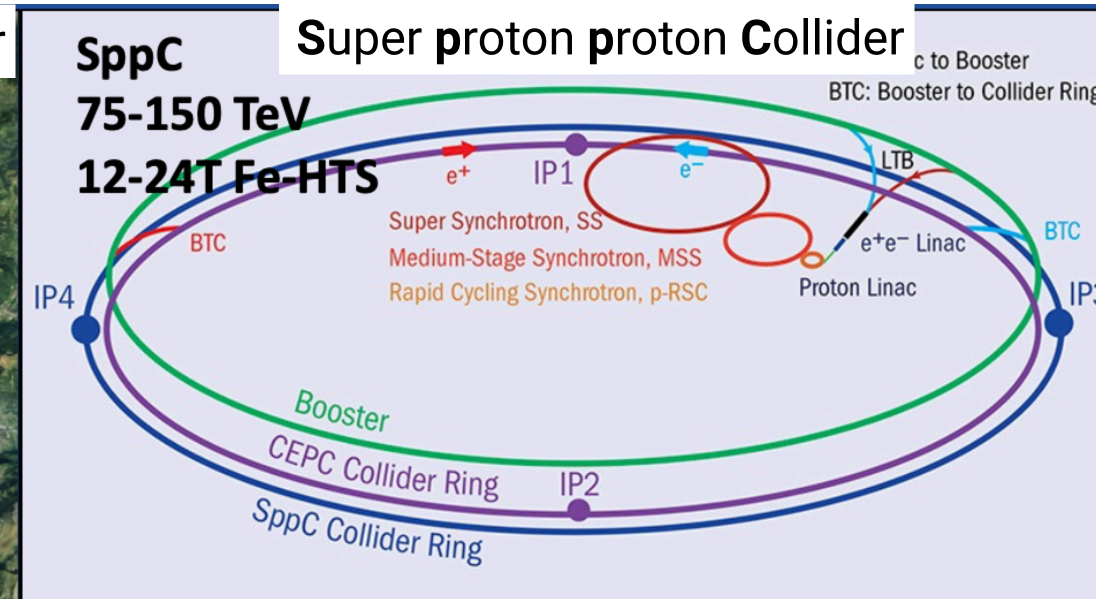
- 250 GeV — *ZH* threshold
- 365 GeV — *tt* threshold
- 10-30 TeV ?? technology limit

- New idea: e^- plasma acceleration, e^+ conventional LinAc
- ca. 10 years R&D needed to demonstrate feasibility
- Extremely compact: 3-4 km size, suitable for national lab

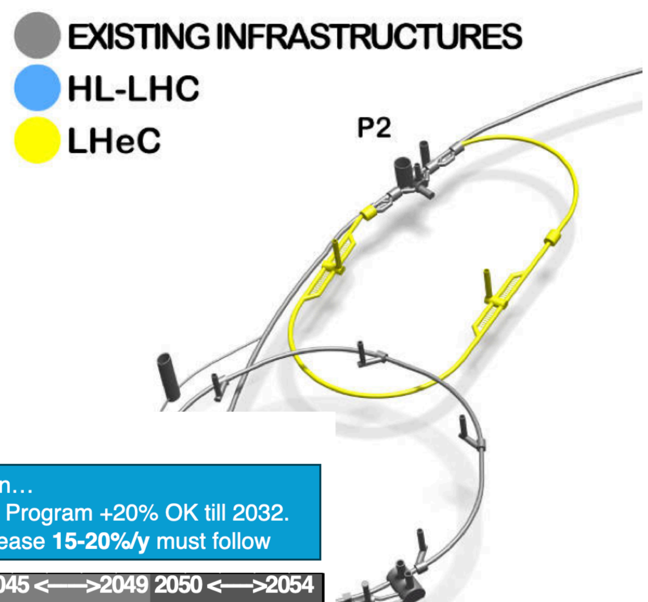
Future hadron colliders

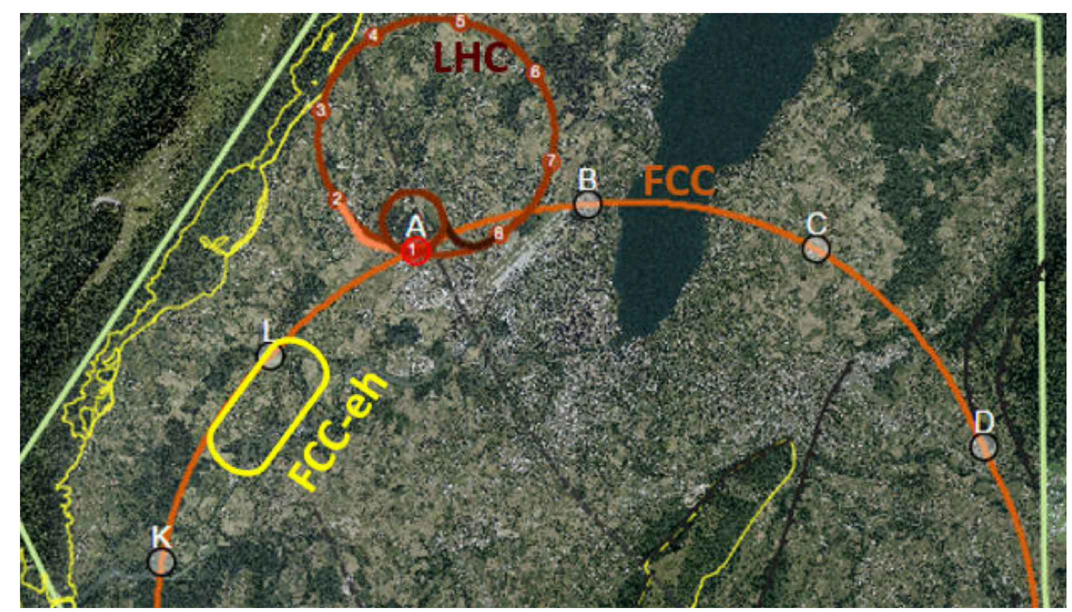


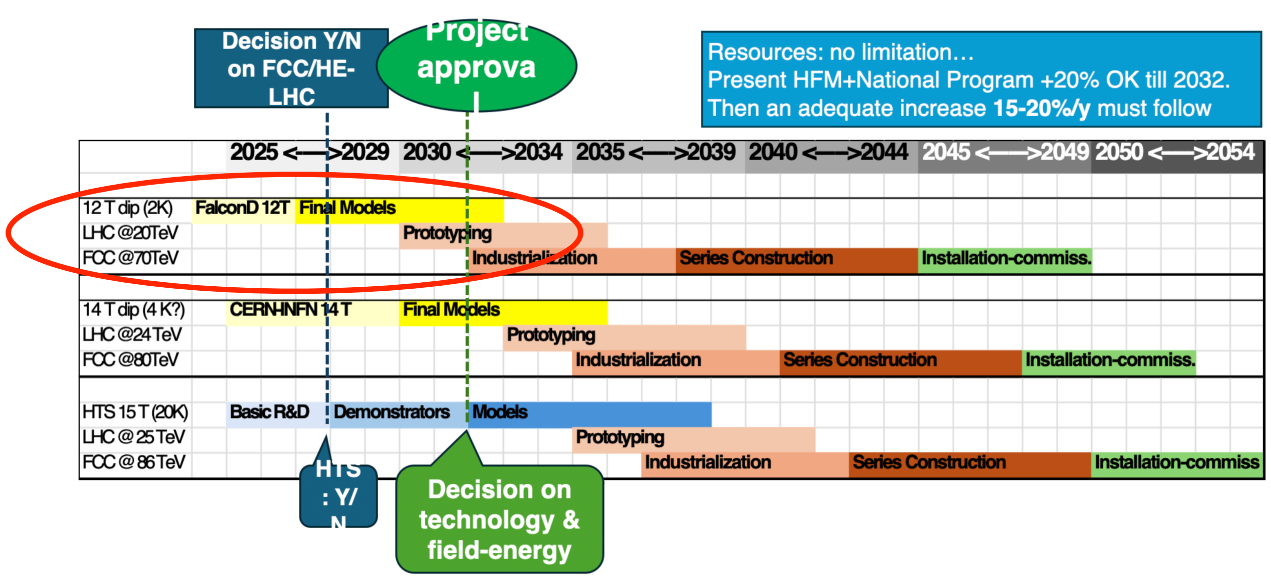




- The main challenge: high-field magnets: ~ 16+ T
- Electron-hadron collisions when combined with ERLs: LHeC, FCC-eh at CERN







[L. Rossi '24]

Higgs couplings to fermions and gauge bosons: the quest for identifying the underlying physics

Couplings of detected Higgs boson to fermions, gauge bosons:

In many BSM models one expects only % level deviations or less from the SM couplings for BSM particles in the TeV range. Example of 2HDM-type model in decoupling limit:

$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} \simeq 1 - 0.3\% \left(\frac{200\ \rm GeV}{m_A}\right)^4$$

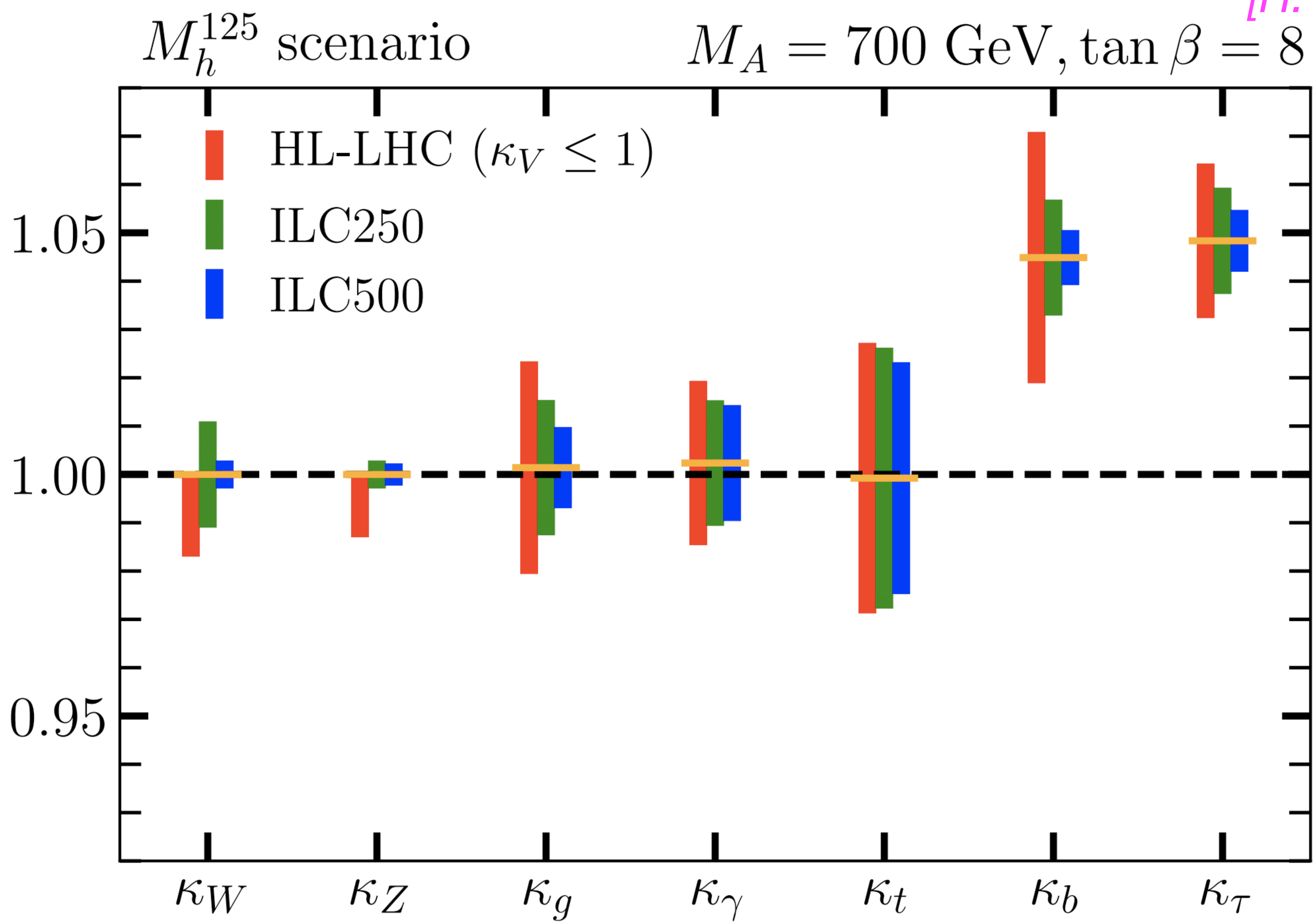
$$\frac{g_{htt}}{g_{h_{\rm SM}tt}} = \frac{g_{hcc}}{g_{h_{\rm SM}cc}} \simeq 1 - 1.7\% \left(\frac{200\ \rm GeV}{m_A}\right)^2$$

$$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 40\% \left(\frac{200\ \rm GeV}{m_A}\right)^2 .$$

⇒ Need very high precision for the couplings

Higgs couplings: example of “heavy” SUSY scenario

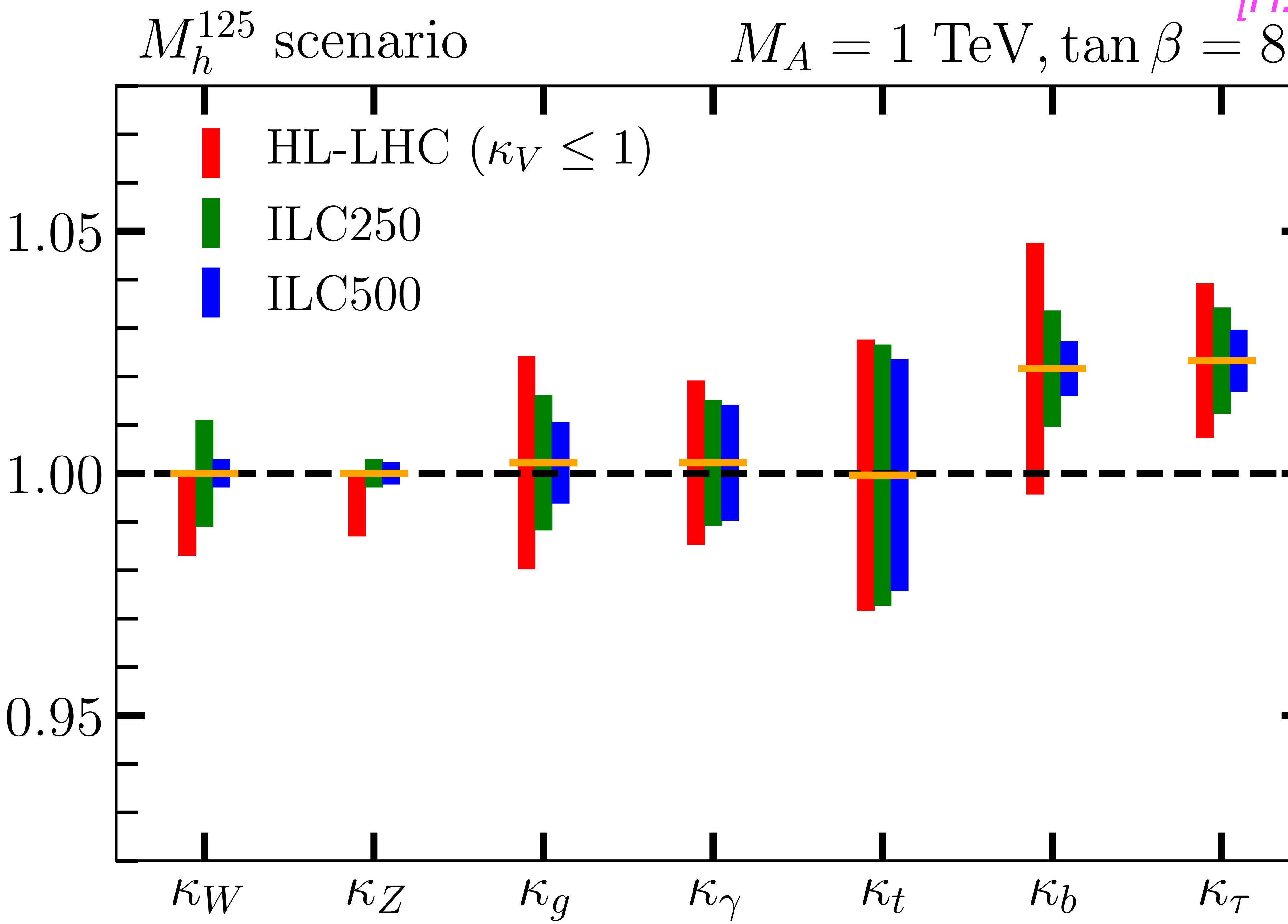
[H. Bahl et al. ’20]



⇒ Need to resolve deviations at the level of 1% or below to get sensitivity to possible effects of BSM physics

Higgs couplings: example of “heavy” SUSY scenario

[H. Bahl et al. ’20]



⇒ Need to resolve deviations at the level of 1% or below to get sensitivity to possible effects of BSM physics

Higgs couplings: towards high precision

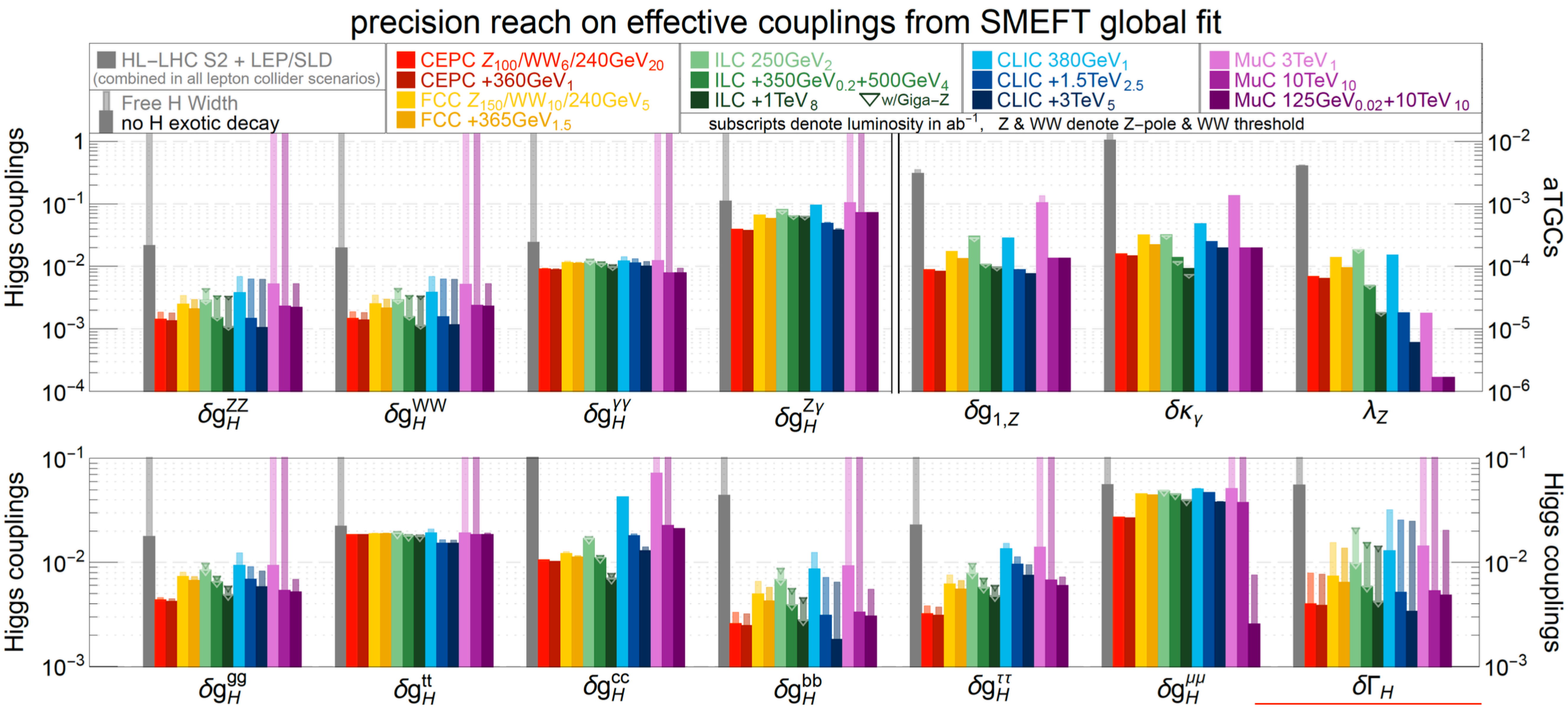
- A coupling is not a physical observable: if one talks about measuring Higgs couplings at the % level or better, one needs to precisely define what is actually meant by those couplings!

- For the determination of an appropriate coupling parameter at this level of accuracy the incorporation of strong and electroweak loop corrections is inevitable. This is in general not possible in a strictly model-independent way!

- For comparisons of present and future facilities it is crucial to clearly spell out under which assumptions these comparisons are done

Global EFT fits: projections for future colliders

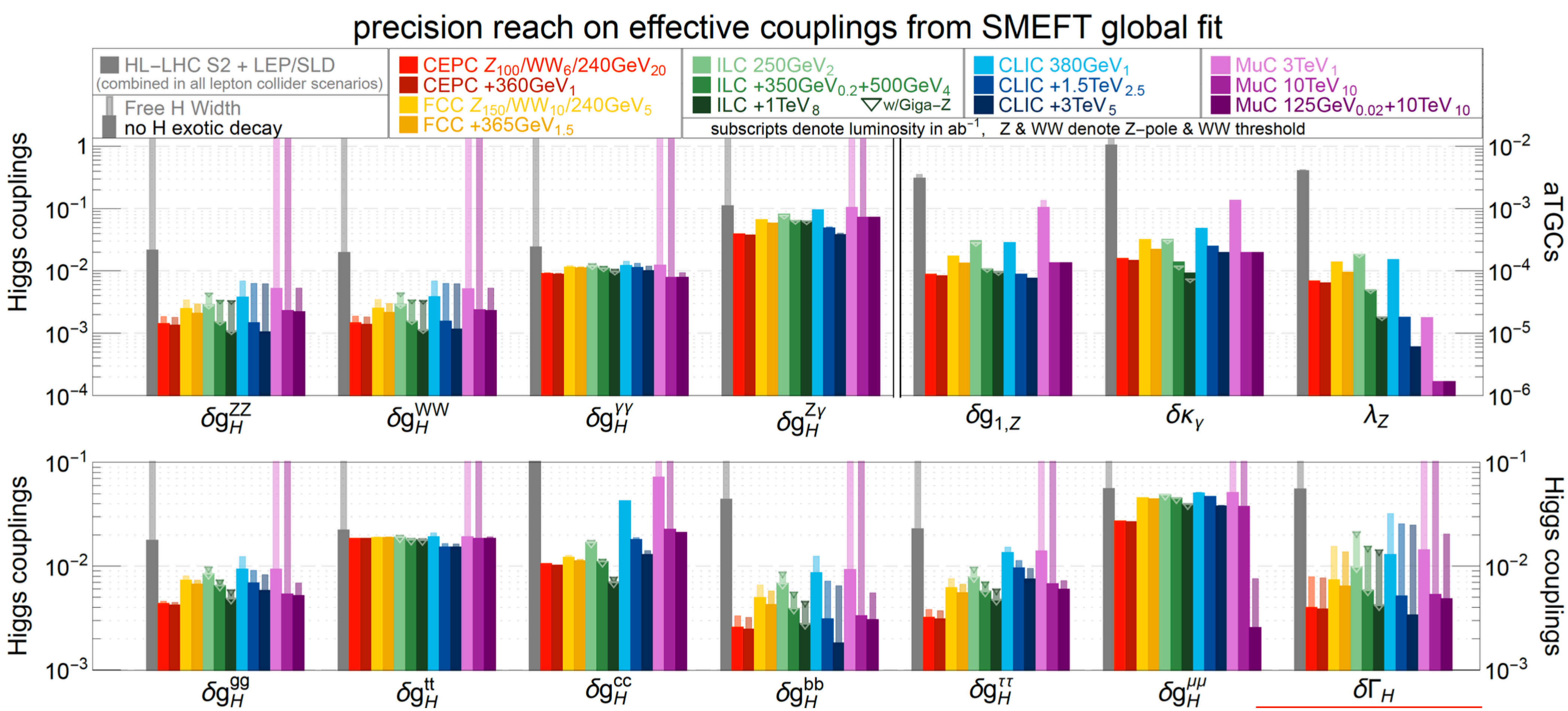
[J. de Blas et al. ’22]



Global EFT fits: projections for future colliders

[J. Reuter '24]

- ☑ All Higgs factories perform similar: luminosity vs. polarization
- ☑ Couplings will be pushed to single percent-few per mille
- ☑ Gain at least one order of magnitude precision over HL-LHC
- ☑ If exotic Higgs decays exist: no absolute couplings from LHC



The quest for identifying the underlying physics

- Future Higgs factories: what can we learn from the enhanced precision in comparison to the direct searches at the HL-LHC (existing limits and future prospects)?

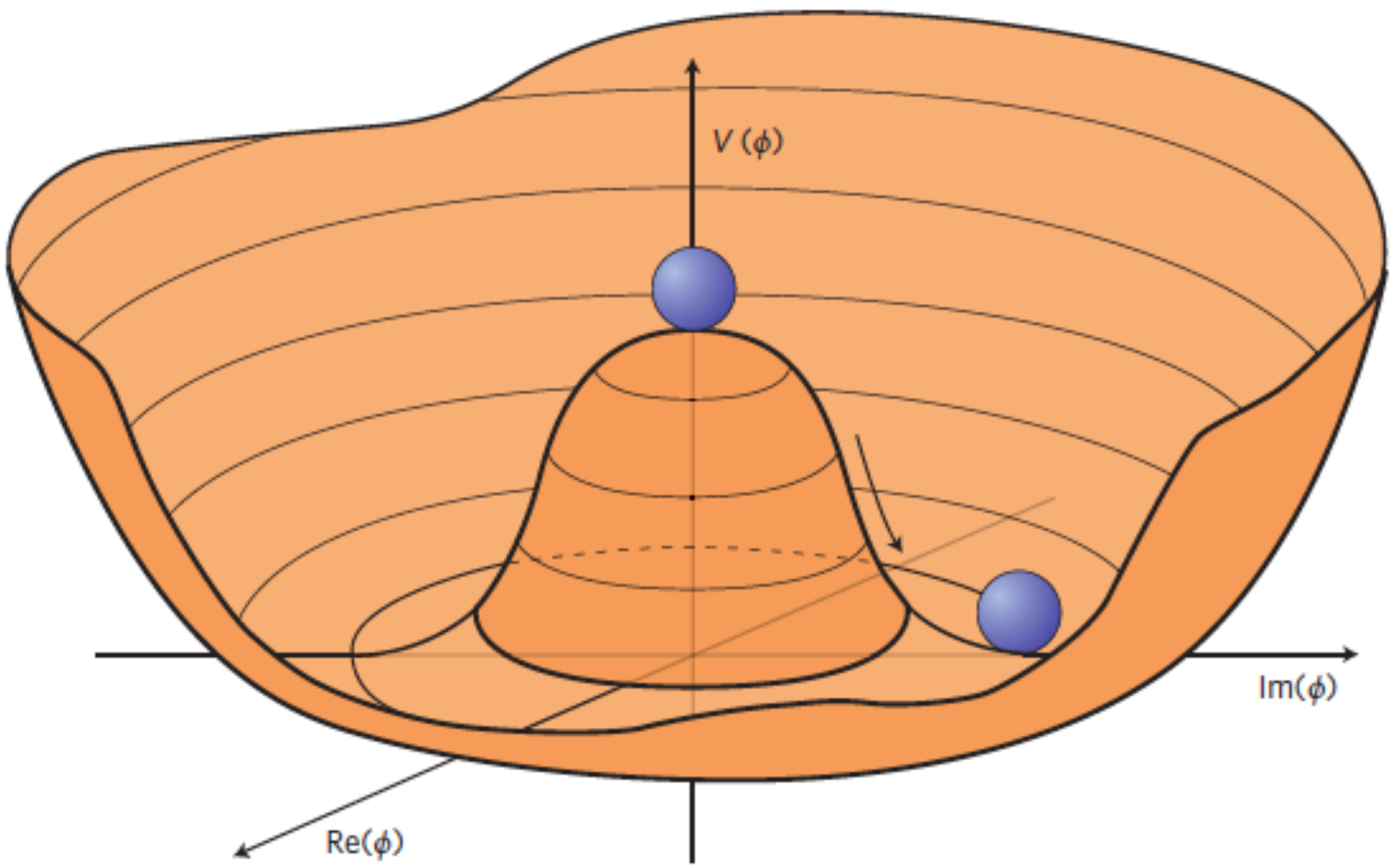
- How significant will possible patterns of deviations be? How stringent are indirect hints for additional particles (typically scale like coupling/mass^2)?

- How well can one distinguish between different realisations of possible BSM physics?

Questions of this kind have hardly been touched upon at the previous update of the European Strategy for Particle Physics, but they are crucial for making the case for a (low-energy) e^+e^- Higgs factory in the wider scientific community!

Higgs potential: the “holy grail” of particle physics

The simple picture



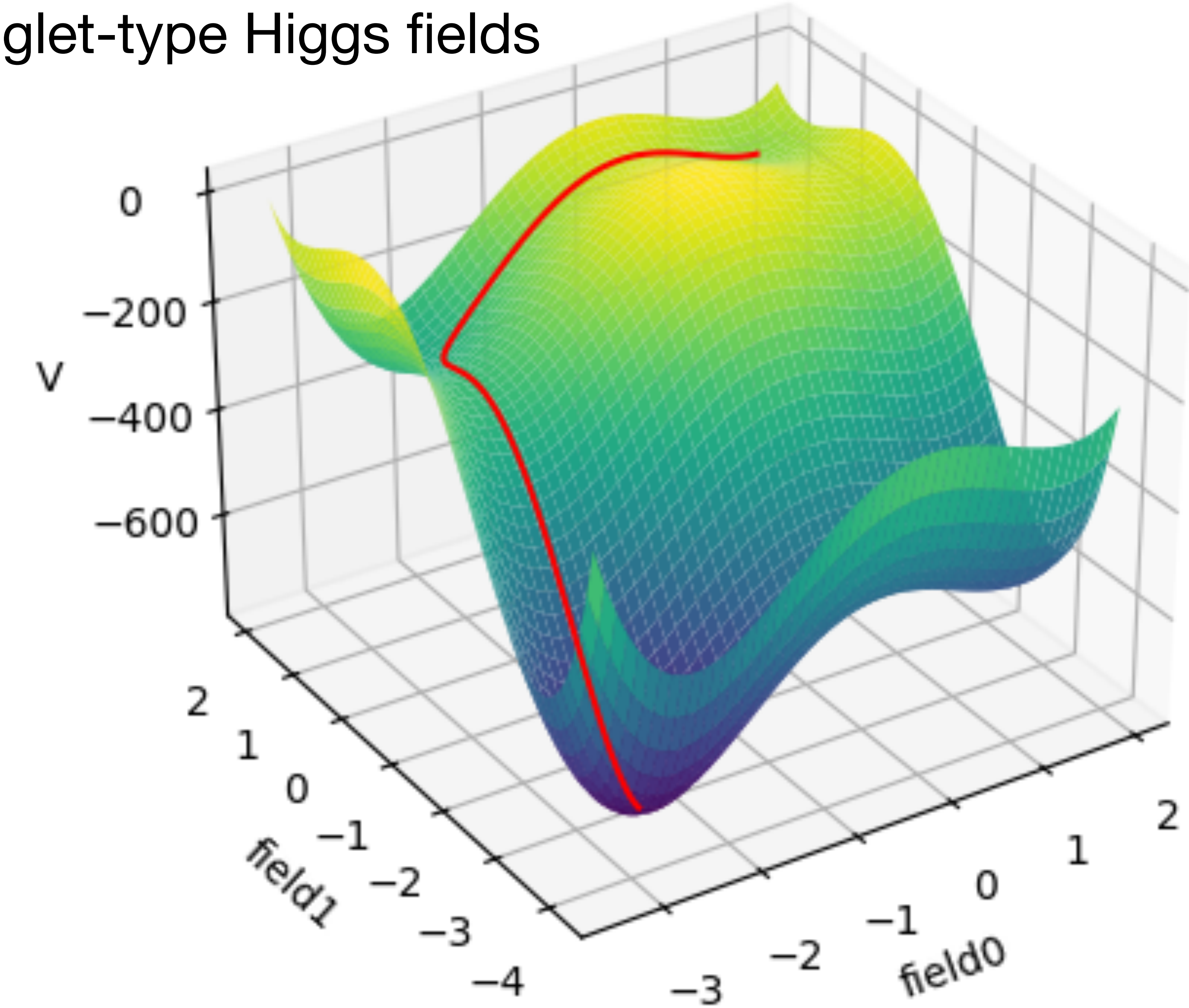
refers to the case of a single Higgs doublet field

If more than one scalar field is present, the Higgs potential is a multi-dimensional function of the components of the different scalar fields

The Higgs potential and vacuum stability

[T. Biekötter, F. Campello, G. W. '24]

Tunneling from a local minimum into the global minimum: toy example, two singlet-type Higgs fields

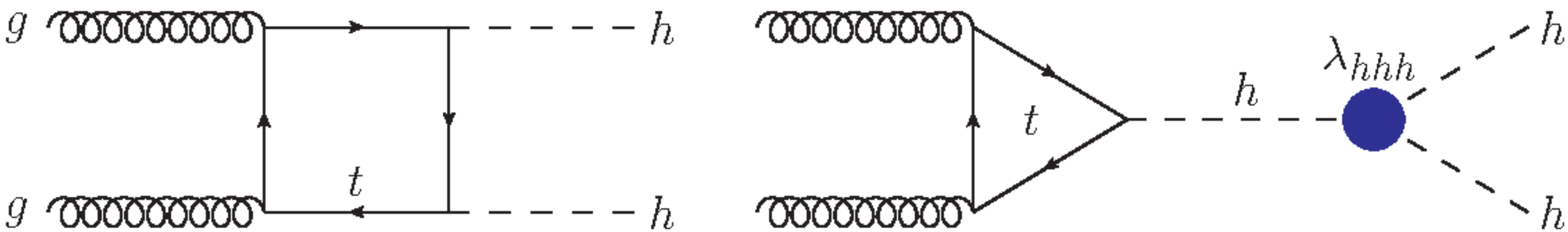


⇒ Proceeds via intermediate local minimum

Trilinear Higgs self-coupling and the Higgs pair production process

Sensitivity to the trilinear Higgs self-coupling from Higgs pair production:

- **Double-Higgs production** → λ_{hhh} enters at LO → **most direct probe of λ_{hhh}**



[Note: Single-Higgs production (EW precision observables) → λ_{hhh} enters at NLO (NNLO)]

Note: the ``non-resonant" experimental limit on Higgs pair production obtained by ATLAS and CMS depends on $\varkappa_\lambda = \lambda_{hhh} / \lambda_{hhh}^{SM, 0}$

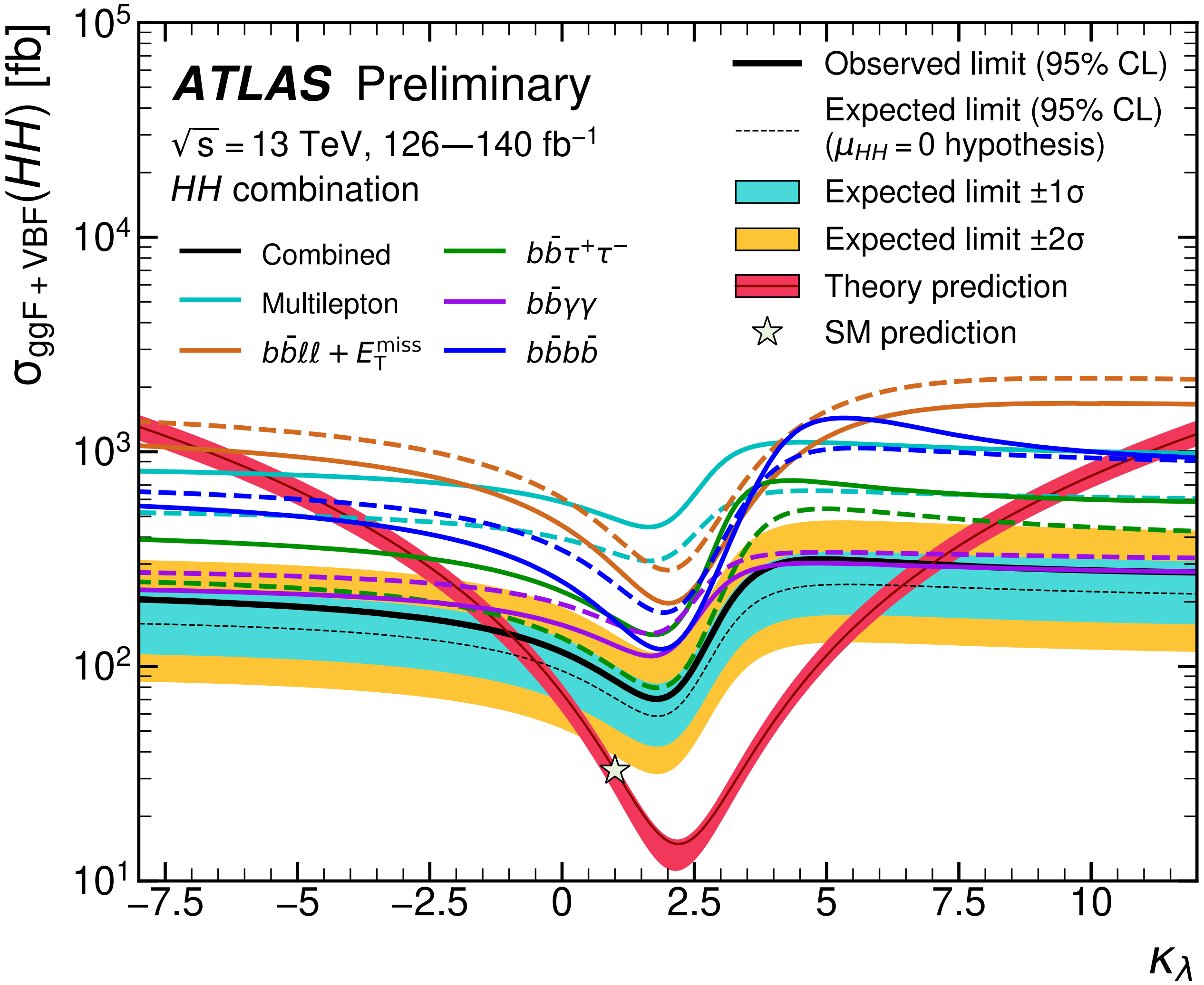
e^+e^- Higgs factory:

Indirect constraints from measurements of single Higgs production and electroweak precision observables at lower energies are not competitive

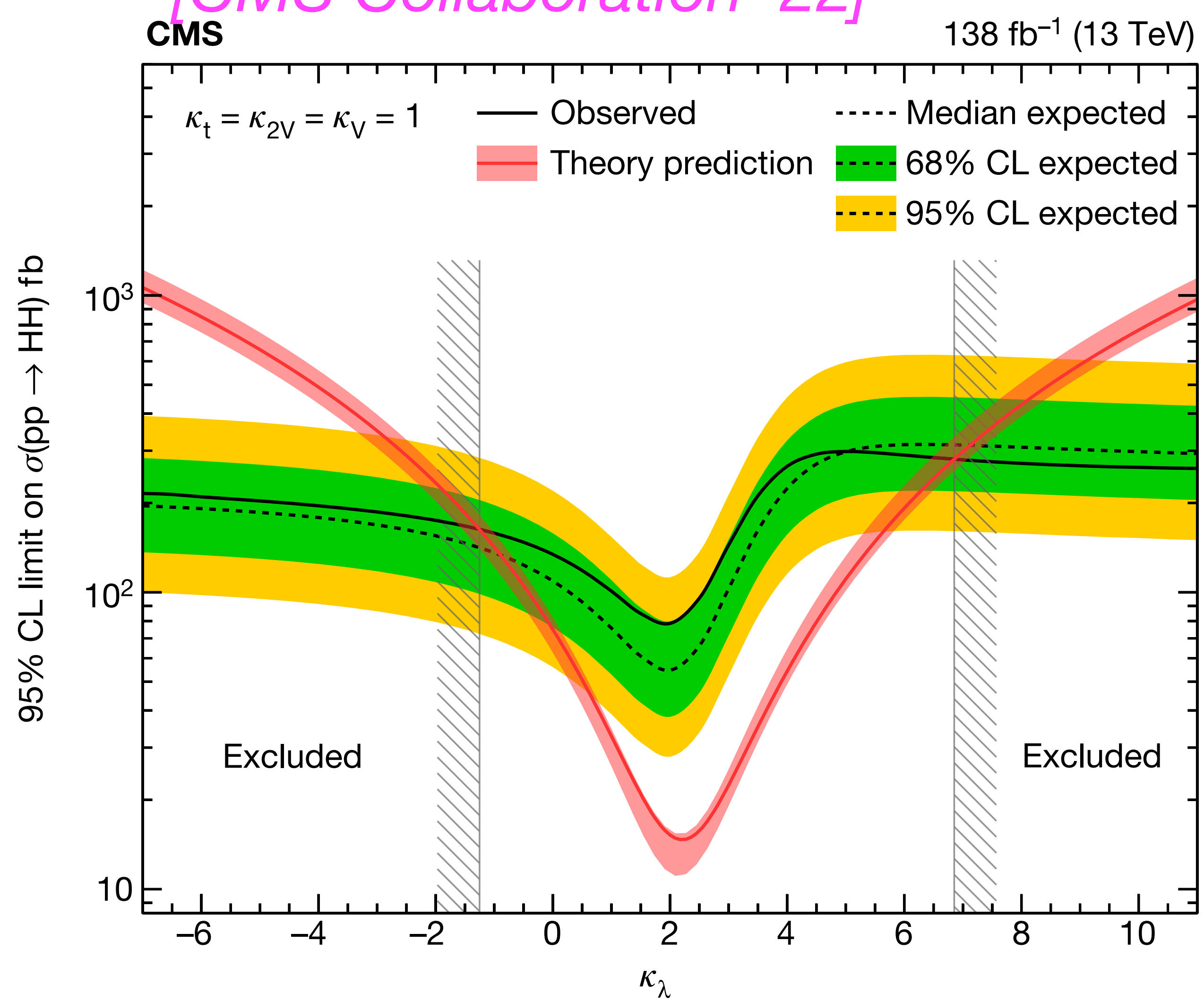
Direct measurement of trilinear Higgs self-coupling is possible a at lepton collider with at least 500 GeV c.m. energy

Bound on the trilinear Higgs self-coupling: $\varkappa_\lambda$

[ATLAS Collaboration '24]



[CMS Collaboration '22]



Using only information from di-Higgs production and assuming that new physics only affects the trilinear Higgs self-coupling, this limit on the cross section translates to:

ATLAS: $-1.2 < \varkappa_\lambda < 7.2$ at 95% C.L. [ATLAS Collaboration '24]

CMS: $-1.2 < \varkappa_\lambda < 6.5$ at 95% C.L. [CMS Collaboration '22]

Check of applicability of the experimental limit on κ_λ

The assumption that new physics only affects the trilinear Higgs self-coupling is expected to hold at most approximately in realistic models

BSM models can modify Higgs pair production via resonant and non-resonant contributions

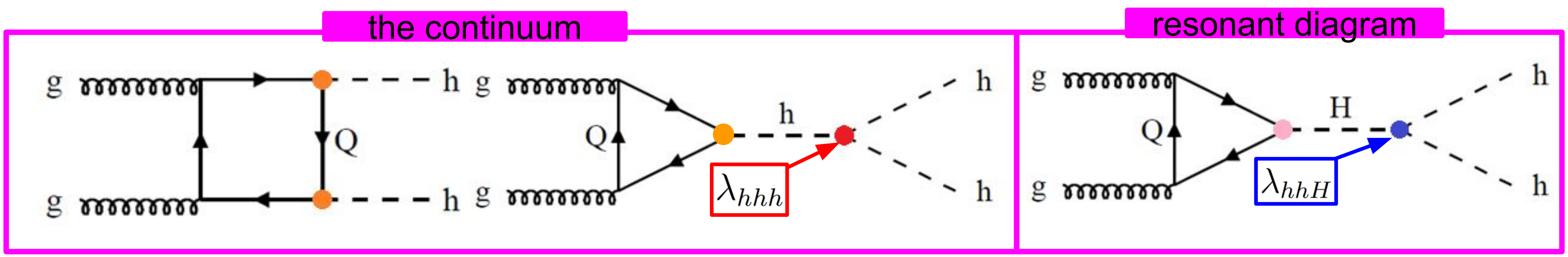
The current experimental limit can only probe scenarios with large deviations from the SM

$\Rightarrow$ Direct application of the experimental limit on κ_λ is possible if sub-leading effects are less relevant

Resonant Higgs pair production

ATLAS and CMS present their ``resonant” limits by ignoring the non-resonant contributions to the signal for Higgs pair production

In all realistic scenarios the resonant contribution is accompanied by the non-resonant contribution, involving h125, giving rise to potentially sizeable interference contributions

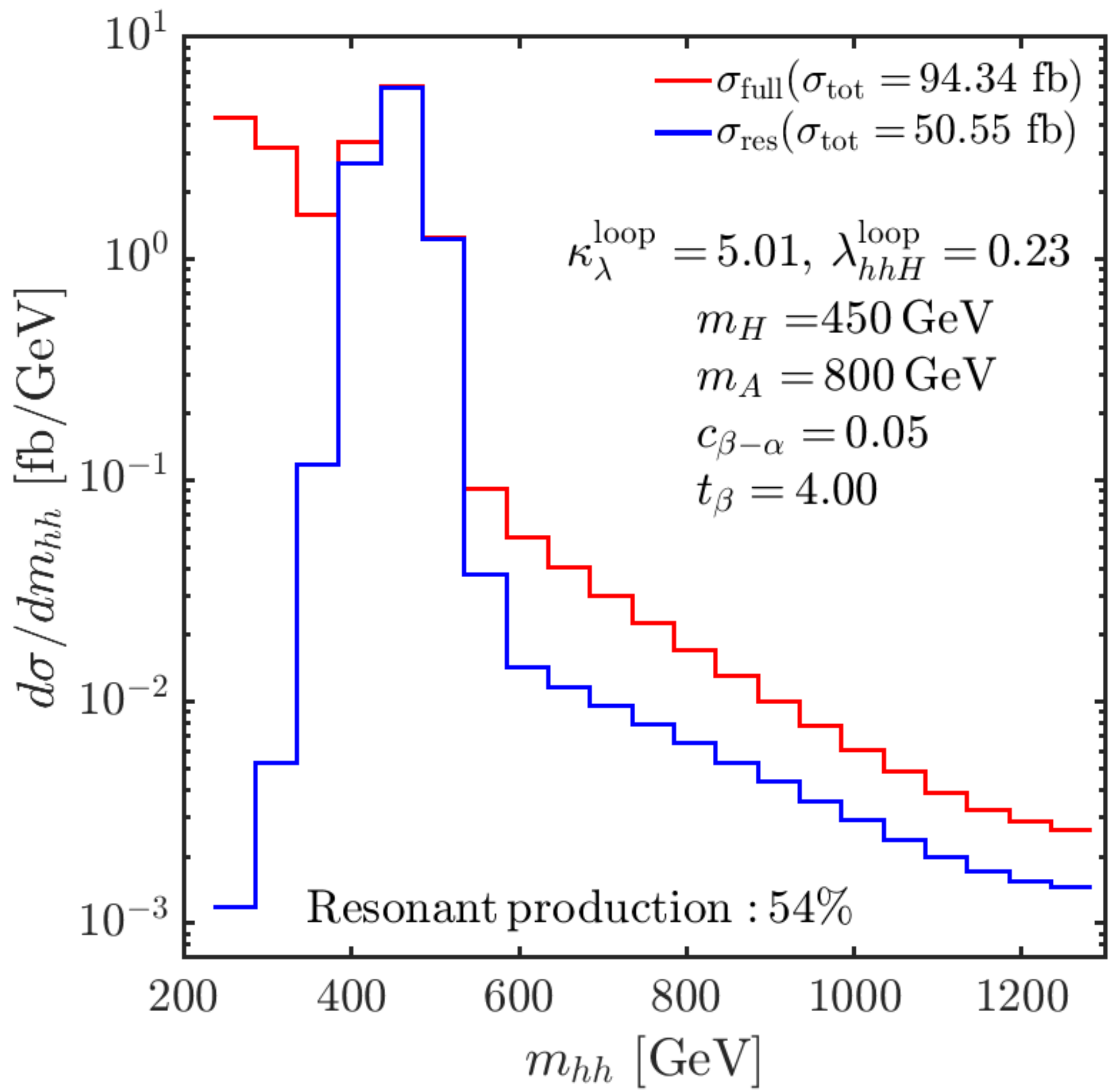


⇒ The experimental results for Higgs pair production have to be such that they can be confronted with realistic theoretical models!

Interference effects in Higgs pair production

[S. Heinemeyer, M. Mühlleitner, K. Radchenko, G. W. '24]

2HDM example, exp. smearing included, scenario that is claimed to be excluded by the resonant LHC searches, full result vs. resonant contrib.



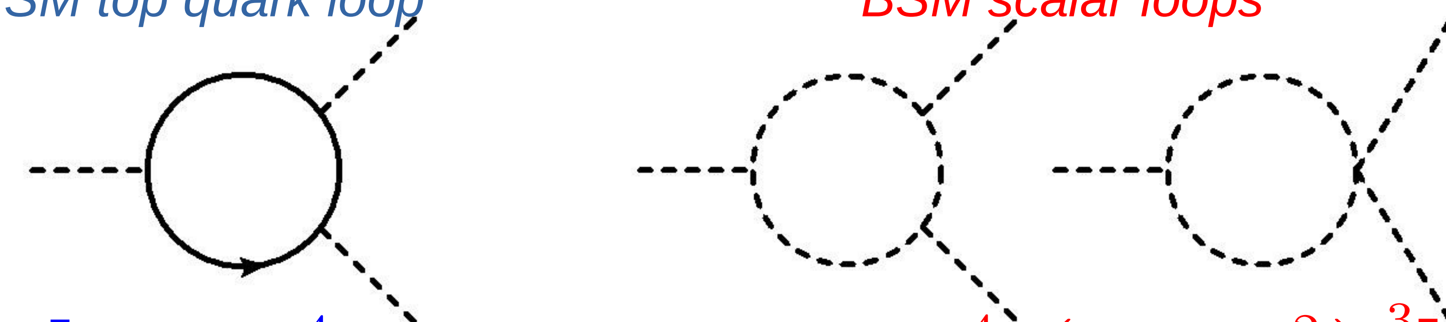
⇒ m_{HH} distribution depends very sensitively on $\varkappa_\lambda$, important interference effects, large deviation between resonant contribution and full result; limits using resonant contribution may be too optimistic

Effects of BSM particles on the trilinear Higgs coupling

Trilinear Higgs coupling in extended Higgs sectors: potentially large loop contributions

- **Leading one-loop** corrections to λ_{hhh} in models with extended sectors (like 2HDM):

SM top quark loop *BSM scalar loops*



$$\delta^{(1)}\lambda_{hhh} \supset \frac{1}{16\pi^2}\left[-\frac{48 m_t^4}{v^3} + \sum_{\Phi} \frac{4 n_\Phi m_\Phi^4}{v^3}\left(1-\frac{\mathcal{M}^2}{m_\Phi^2}\right)^3\right]$$

First found in 2HDM:
[Kanemura, Kiyoura, Okada, Senaha, Yuan '02]

$\mathcal{M}$: **BSM mass scale**, e.g. soft breaking scale M of Z_2 symmetry in 2HDM
n_Φ : # of d.o.f of field Φ

- Size of new effects depends on how the BSM scalars acquire their mass: $m_\Phi^2 \sim \mathcal{M}^2 + \tilde{\lambda} v^2$

⇒ Large effects possible for sizeable splitting between m_Φ and $\mathcal{M}$

Two-loop predictions for the trilinear Higgs coupling in the 2HDM vs. current experimental bounds

[H. Bahl, J. Braathen, G. W. '22]

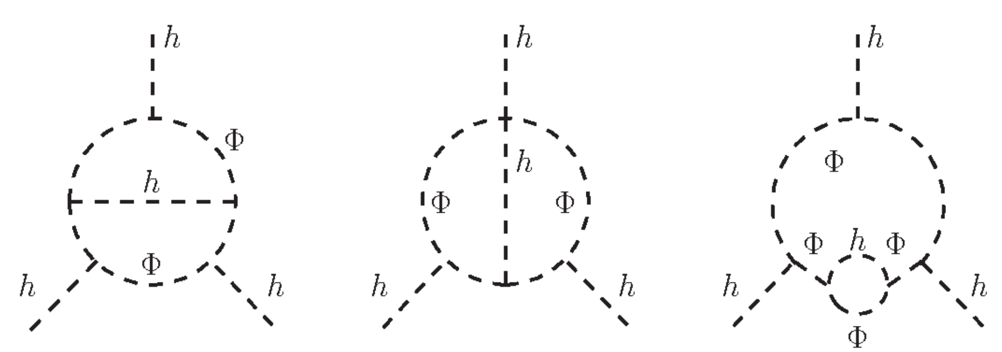
The largest loop corrections to λ_{hhh} in the 2HDM are induced by the quartic couplings between two SM-like Higgs bosons h (where one external Higgs is possibly replaced by its vacuum expectation value) and two BSM Higgs bosons ϕ of the form

$$g_{hh\Phi\Phi} = -\frac{2(M^2 - m_\Phi^2)}{v^2} \qquad \Phi \in \{H, A, H^\pm\}$$

Leading two-loop corrections involving heavy BSM Higgses and the top quark in the effective potential approximation

[J. Braathen, S. Kanemura '19, '20]

⇒Incorporation of the highest powers in $g_{hh\phi\phi}$



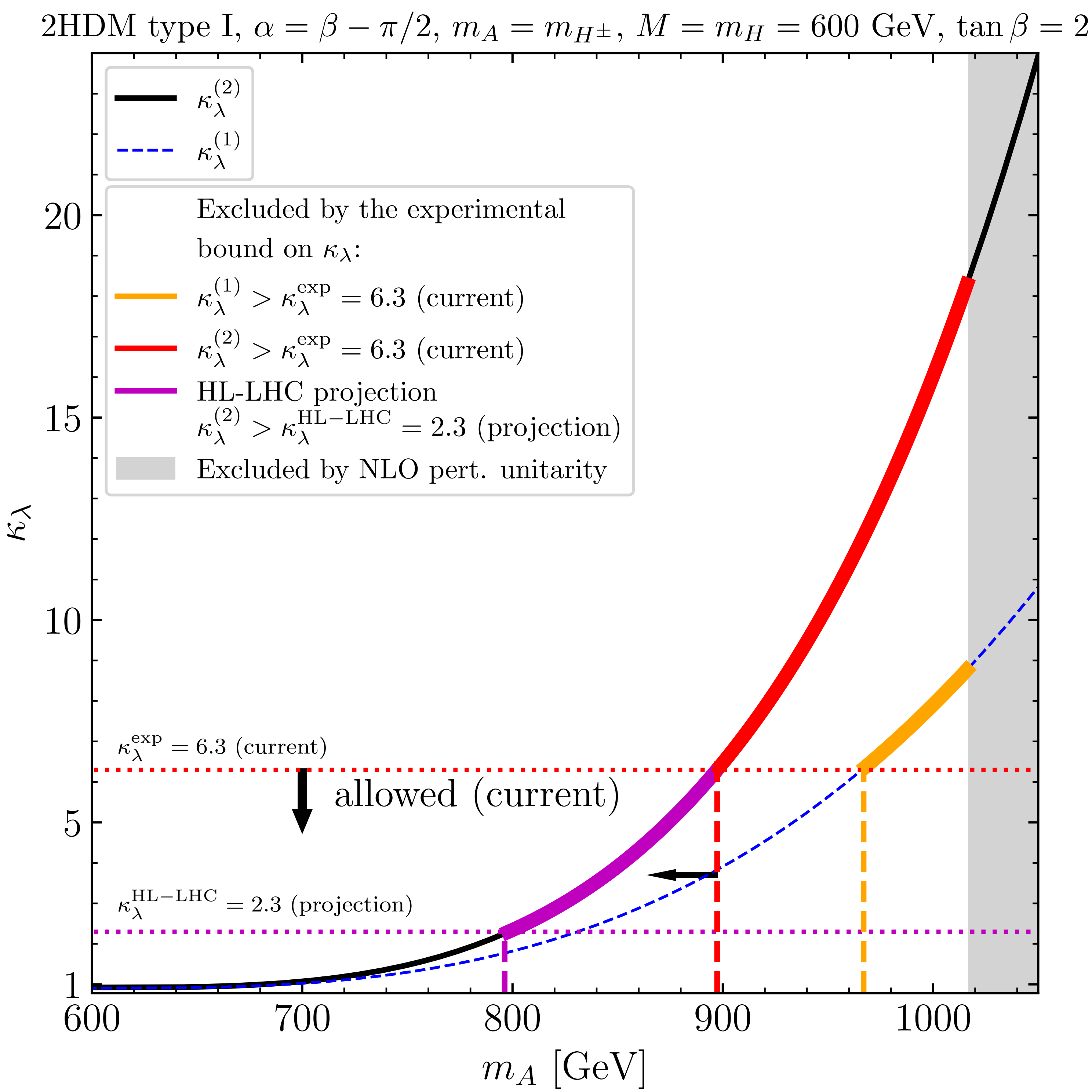
Analysis is carried out in the alignment limit of the 2HDM ($\alpha = \beta - \pi/2$)

⇒h has SM-like tree-level couplings

Trilinear Higgs coupling: current experimental limit vs. prediction from extended Higgs sector (2HDM)

Prediction for $\varkappa_\lambda$ up to the two-loop level:

[H. Bahl, J. Braathen, G. W. '22, Phys. Rev. Lett. 129 (2022) 23, 231802]



⇒ Current experimental limit excludes important parameter region that would be allowed by all other constraints!

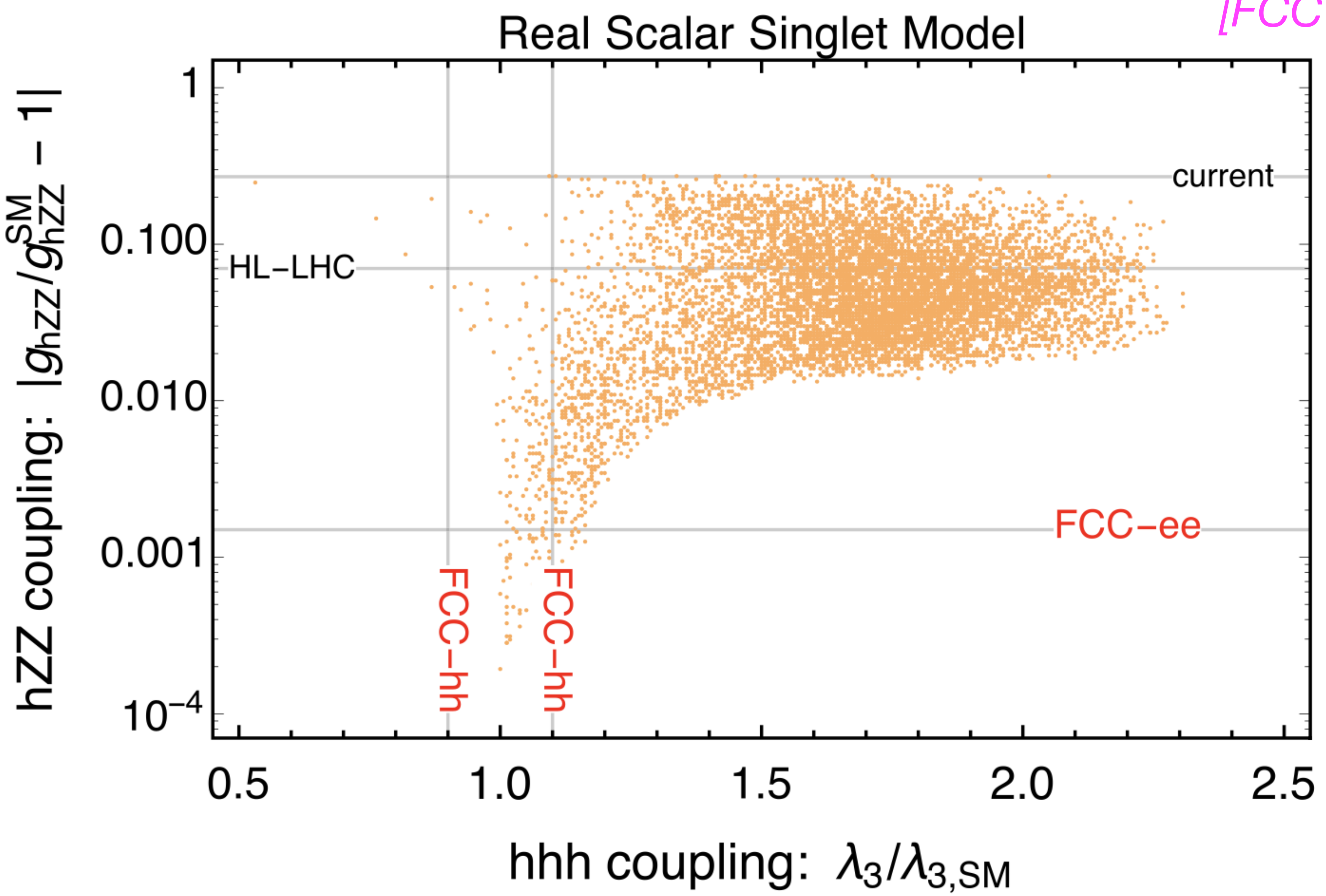
Experimental limit on the trilinear Higgs coupling already has sensitivity to probe extended Higgs sectors!

Correlation of deviations in $\varkappa_\lambda$ with effects in other couplings? Real scalar singlet model

This plot caused some discussions in the context of strategies for future colliders (displayed points feature a FOEWPT):

[FCC Midterm Report '24]

[P. Huang, A. Long, L. Wang '16]

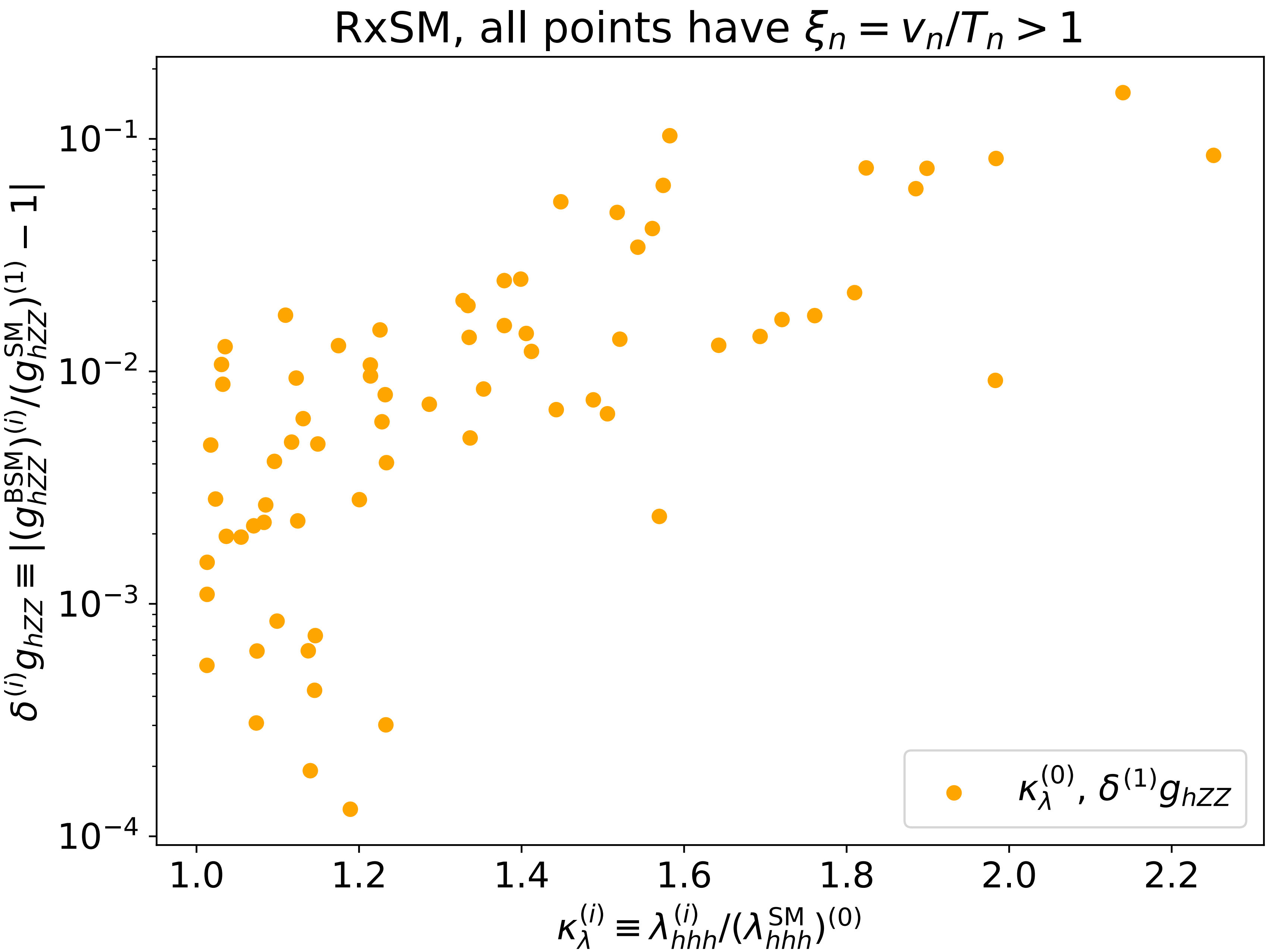


⇒Do the deviations in $\varkappa_\lambda$ have to be small if the FCC-ee does not find a deviation in the h125 coupling to ZZ?

Correlation of deviations in $\varkappa_\lambda$ with effects in other couplings? Real scalar singlet model

[H. Bahl et al. '24]
[work in progress]

Previous plot: no higher-order contributions to $\varkappa_\lambda$ included
New scan (displayed points feature a FOEWPT):

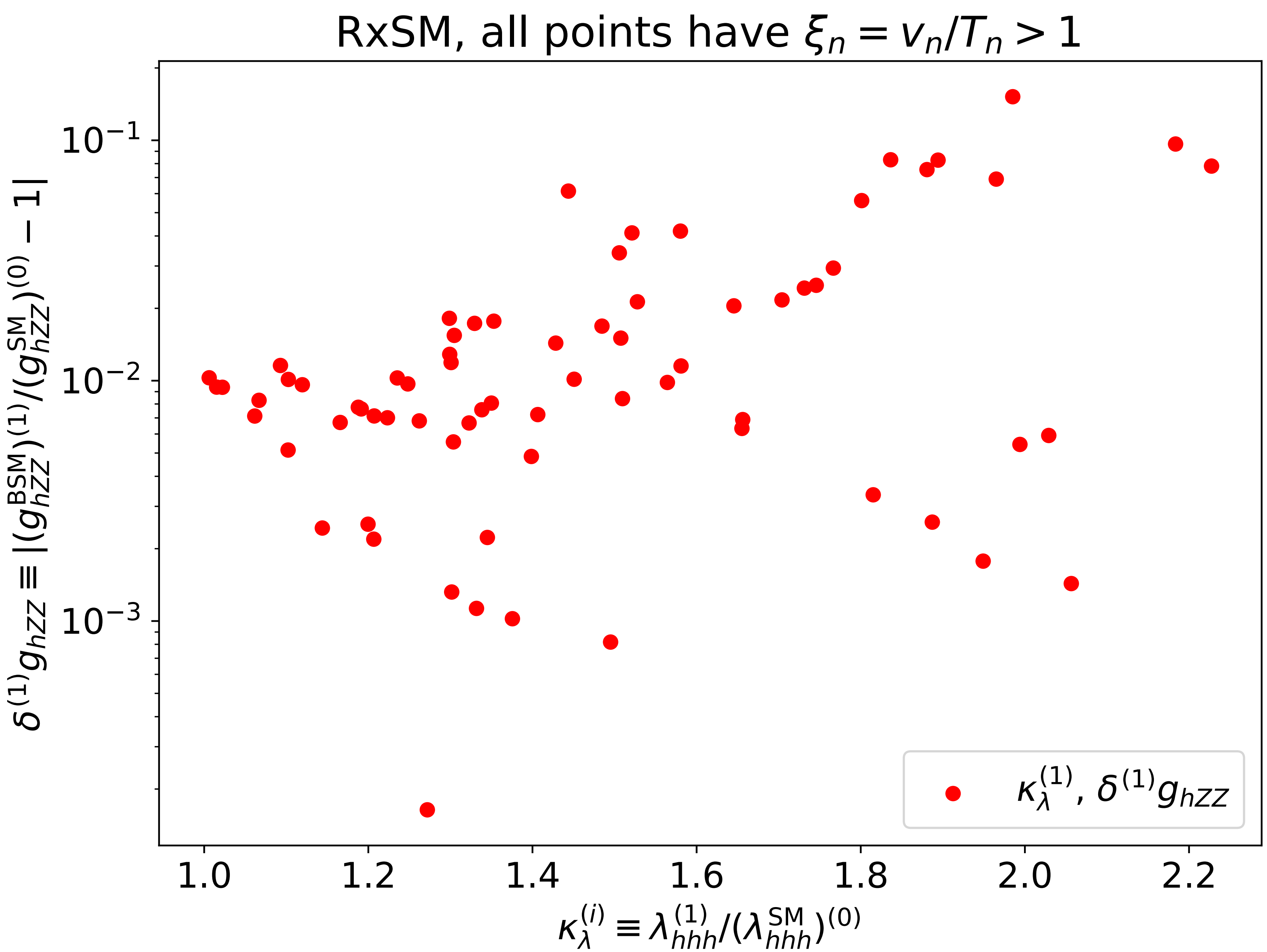


⇒Good agreement with previous plot if higher-order corrections to $\varkappa_\lambda$ are neglected

Correlation of deviations in $\varkappa_\lambda$ with effects in other couplings? Real scalar singlet model

[H. Bahl et al. '24]
[work in progress]

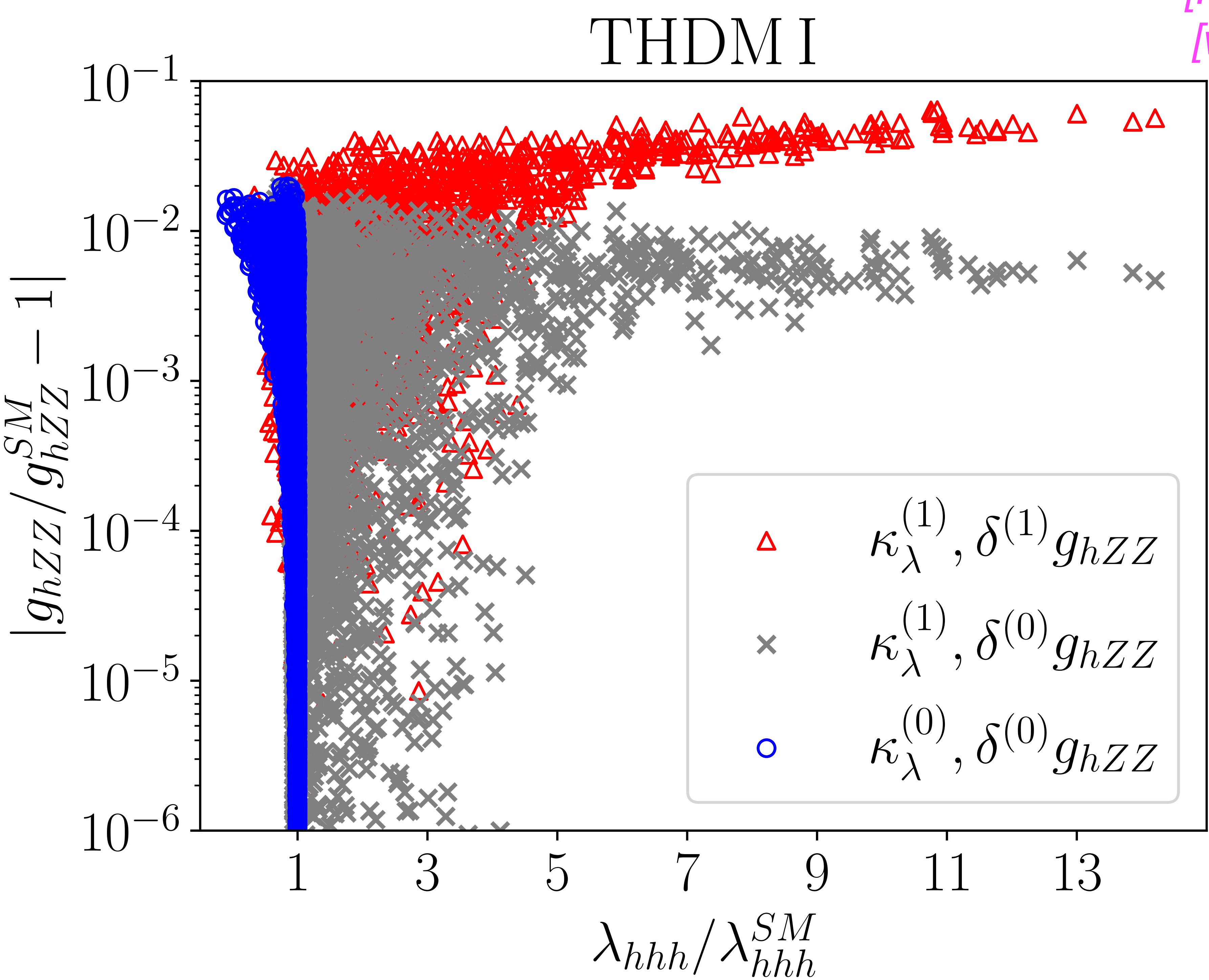
Previous plot: no higher-order contributions to $\varkappa_\lambda$ included
Effect of one-loop corrections (displayed points feature a FOEWPT):



⇒Large deviations in $\varkappa_\lambda$ possible for effects in g_{hZZ} below the FCC sensitivity

Correlation of deviations in $\varkappa_\lambda$ with effects in other couplings? Two Higgs Doublet model

[H. Bahl et al. '24]
[work in progress]



⇒Large deviations in $\varkappa_\lambda$ possible for effects in g_{hZZ} below the FCC sensitivity

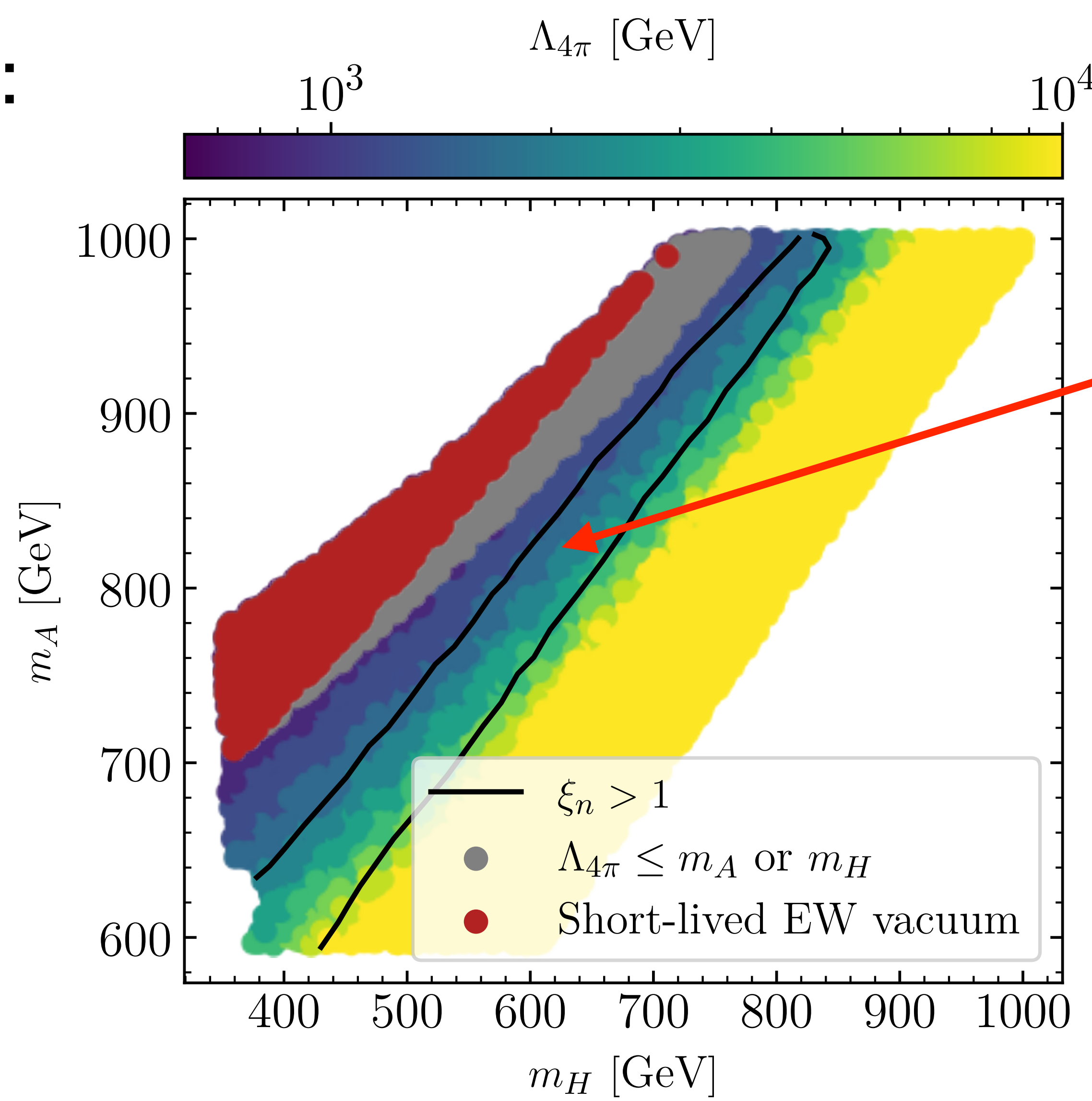
Connection between the trilinear Higgs coupling and the evolution of the early Universe

2HDM, N2HDM, … : the parameter region giving rise to a strong first-order EWPT, which may cause a detectable gravitational wave signal, is correlated with an enhancement of the trilinear Higgs self-coupling and with ``smoking gun” signatures at the LHC

[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. ’22]

2HDM of type II:

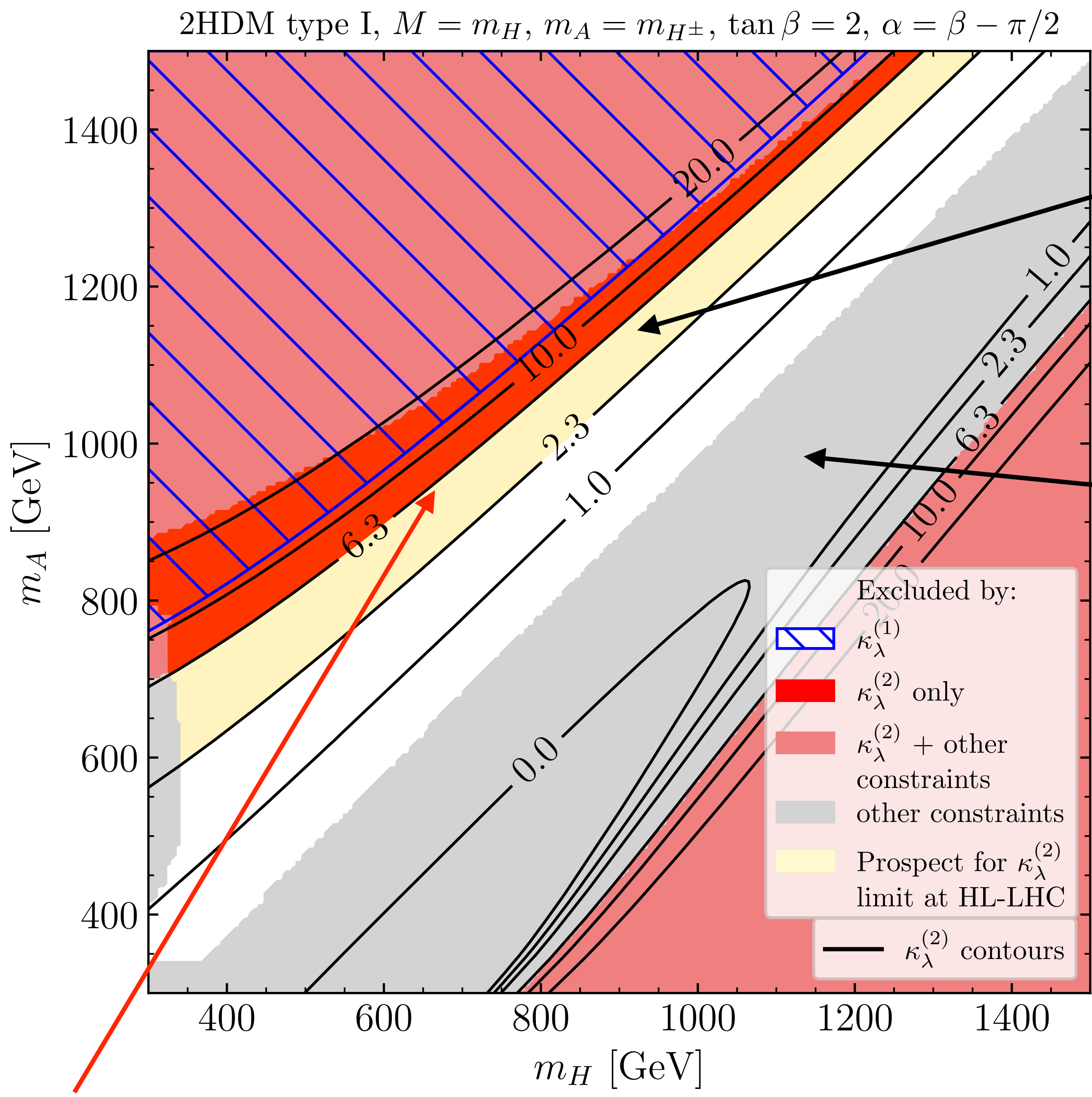
alignment limit,
tanβ = 3



Parameter region giving rise to a strong first-order EWPT

Constraints in the mass plane of H and A

[H. Bahl, J. Braathen, G. W. ’22]



Sensitivity to $\varkappa_\lambda$ at the HL-LHC

Excluded by other constraints:
Higgs physics,
boundedness from below,
NLO perturbative unitarity, …

⇒ LHC limits exclude parameter regions that would be allowed by all other constraints; high sensitivity of future limits / measurements!

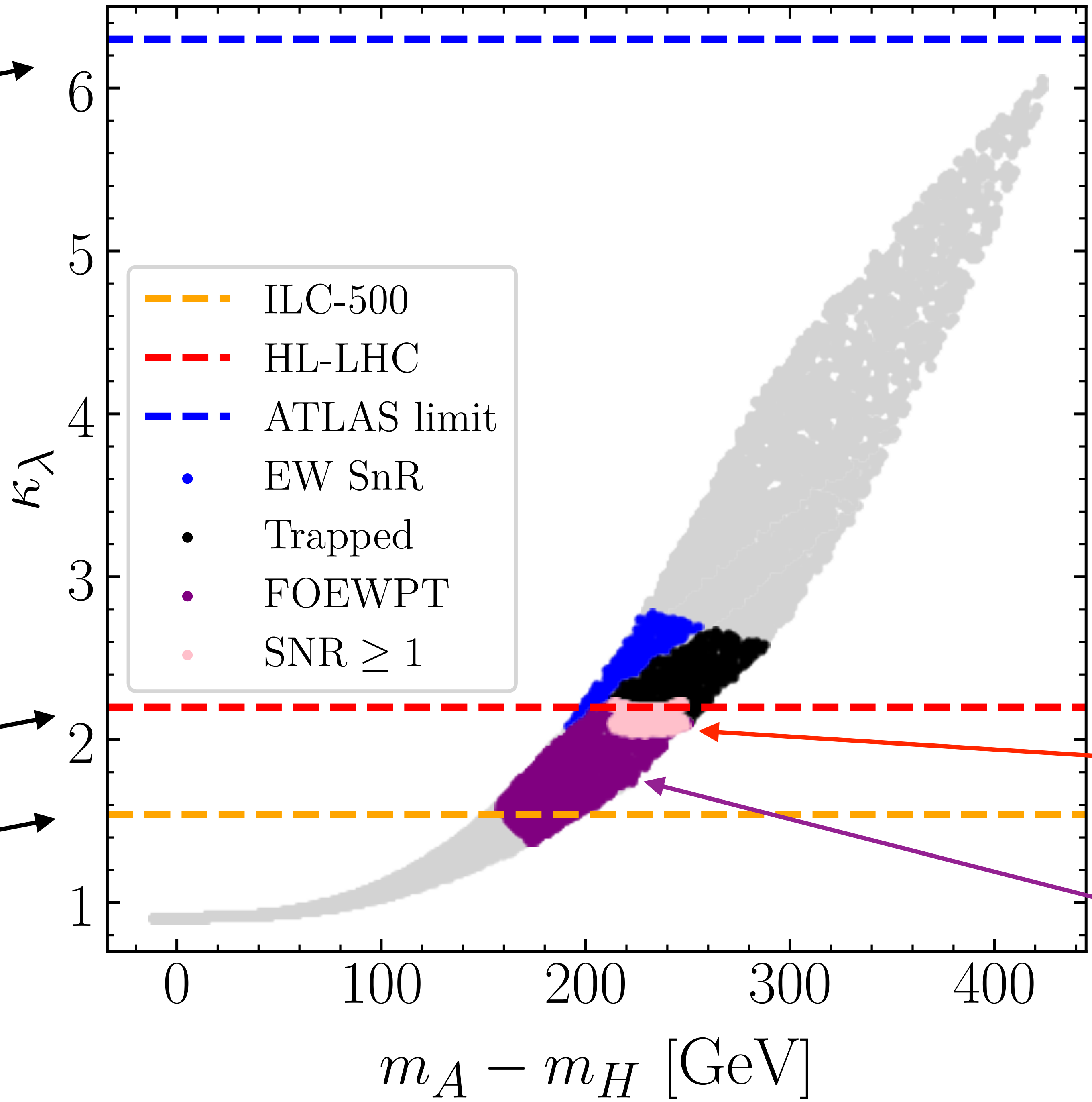
Relation between trilinear Higgs coupling and strong first-order EWPT with potentially observable GW signal

[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. '22]

current bound

HL-LHC sensitivity

ILC sensitivity



alignment limit,
tanβ = 3,
1-loop prediction

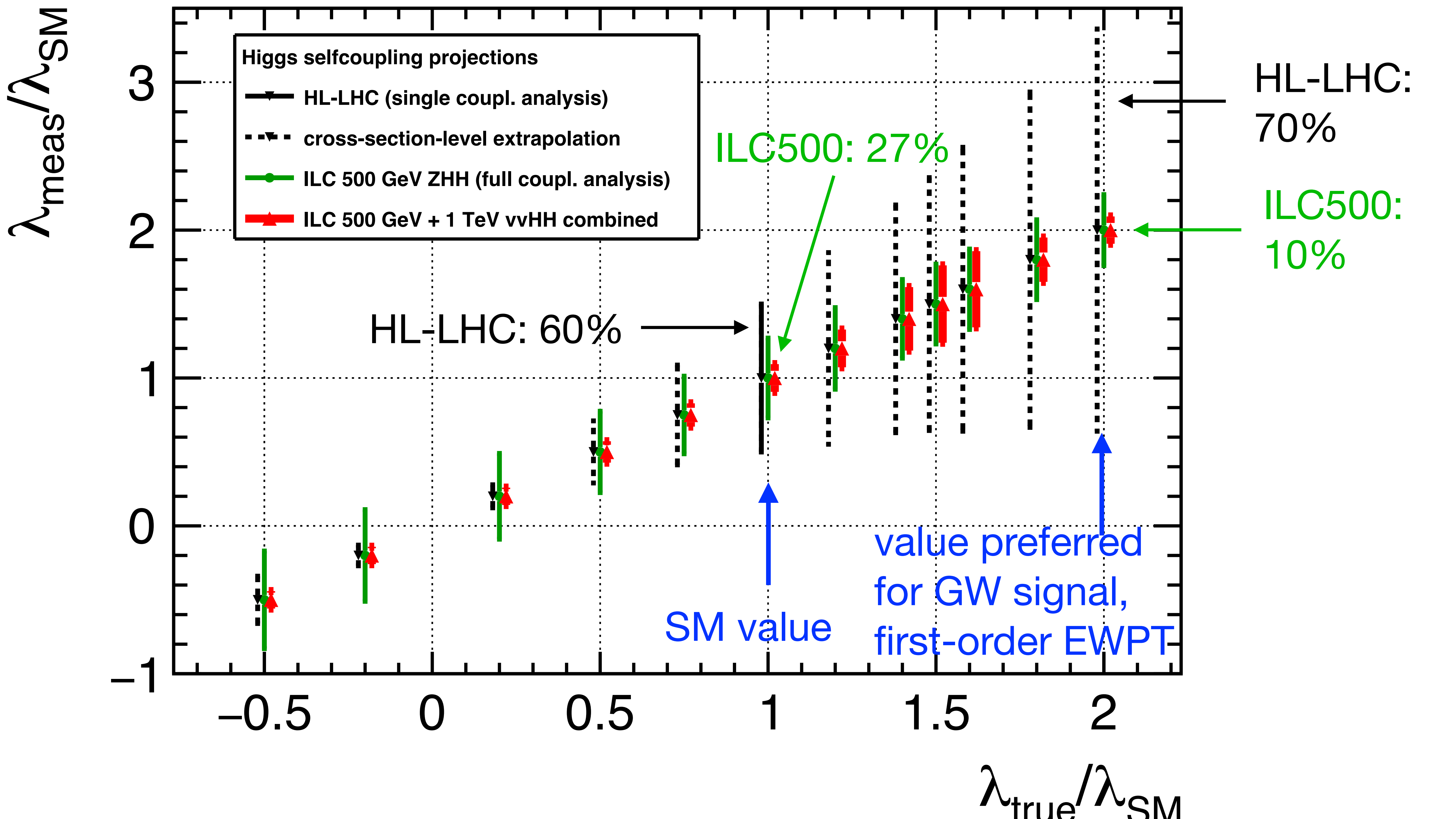
region with potentially observable gravitational wave (GW) signal

region with strong first-order EWPT

⇒ Region with potentially detectable GW signal and strong first-order EWPT is correlated with significant deviation of κ_λ from SM value

Prospects for measuring the trilinear Higgs coupling: HL-LHC vs. ILC (500 GeV, Higgs pair production)

[J. List et al. '21]

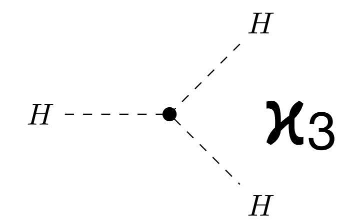


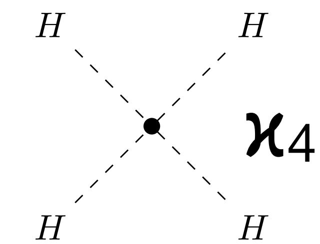
⇒ For $\varkappa_\lambda \approx 2$: much better prospects for ILC500 than for HL-LHC

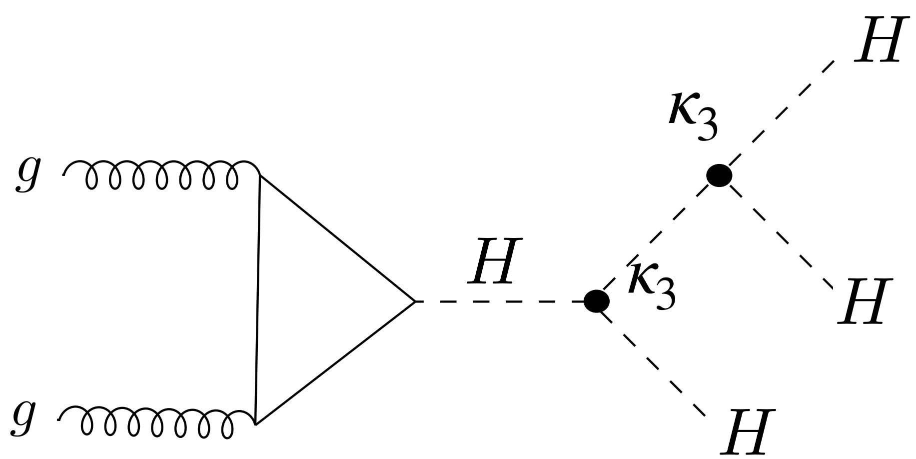
Reason: different interference contributions

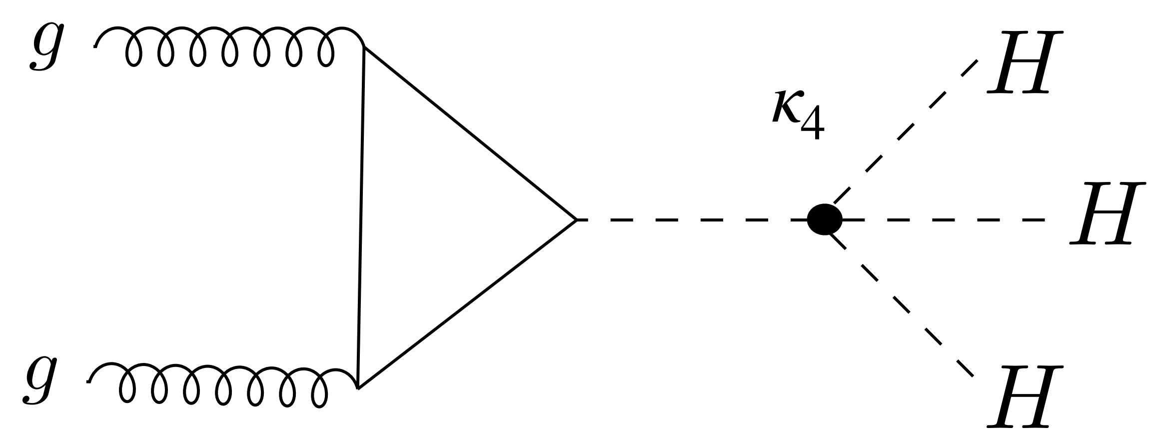
Exploring HHH production w.r.t. Higgs self-couplings

Triple Higgs production depends on $\varkappa_3$ and $\varkappa_4$!









Is it possible to obtain bounds from triple Higgs production on $\varkappa_3$ and $\varkappa_4$ that go beyond the existing theoretical bounds from perturbative unitarity? Potential for $\varkappa_3$ constraints beyond the ones from di-Higgs production?

How big could the deviations in $\varkappa_4$ from the SM value (= 1) be in BSM scenarios?

Bounds from perturbative unitarity

- Process relevant for κ_3, κ_4 is $HH \to HH$ scattering (see also [Liu et al ` 18])

- Jacob-Wick expansion allows to extract partial waves

$$\boxed{\beta(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2xz}$$

Wigner functions

$$a^J_{fi} = \frac{\beta^{1/4}(s, m^2_{f_1}, m^2_{f_1})\beta^{1/4}(s, m^2_{i_1}, m^2_{i_1})}{32\pi s} \int_{-1}^{1} \mathrm{d}\cos\theta\, \mathcal{D}^J_{\mu_i \mu_f}\, \mathcal{M}(s, \cos\theta)$$

- Tree level unitarity:

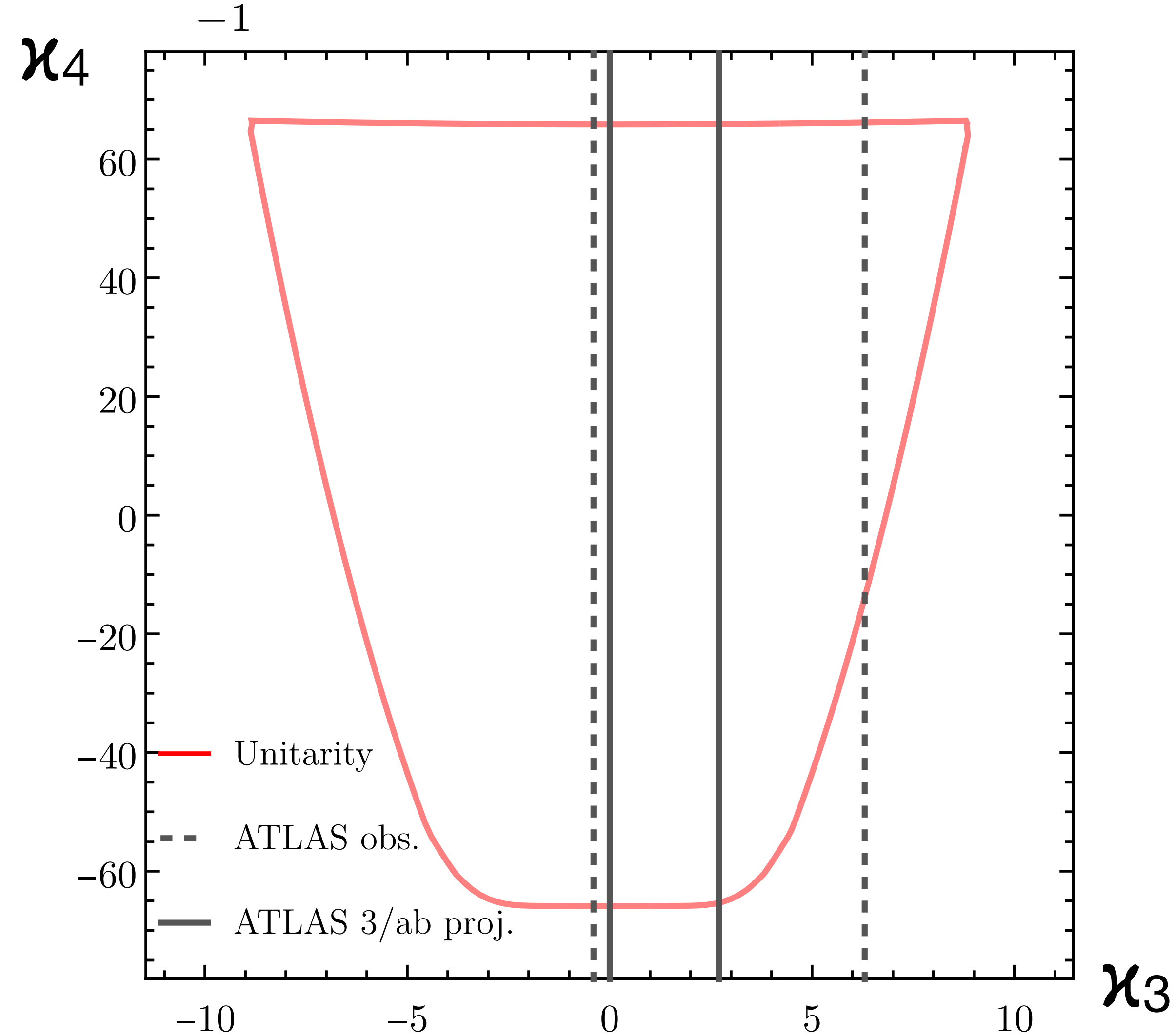
$$\mathrm{Im} a^0_{ii} \geq |a^0_{ii}|^2 \implies |\mathrm{Re} a^0_{ii}| \leq \frac{1}{2}$$

95 % CL

ATLAS current bounds: $[-0.4, 6.3]$

CMS & ATLAS HH projections: $[0.1, 2.3]$

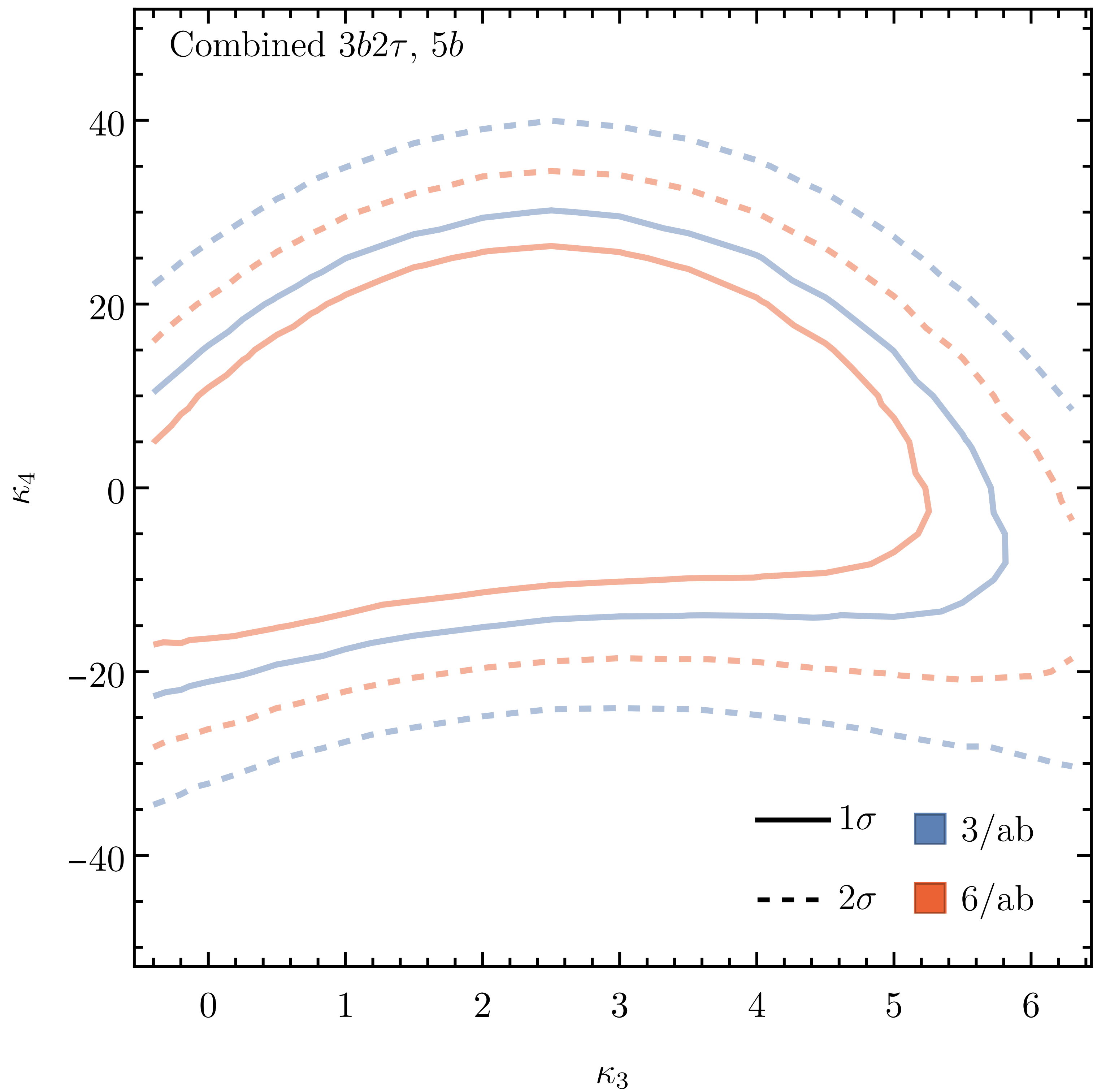
[ATLAS 2211.01216]
[CERN Yellow Rep. 1902.00134]



Prospects for the HL-LHC: 6b and 4b2τ channels comb.

[P. Stylianou, G. W. '24]

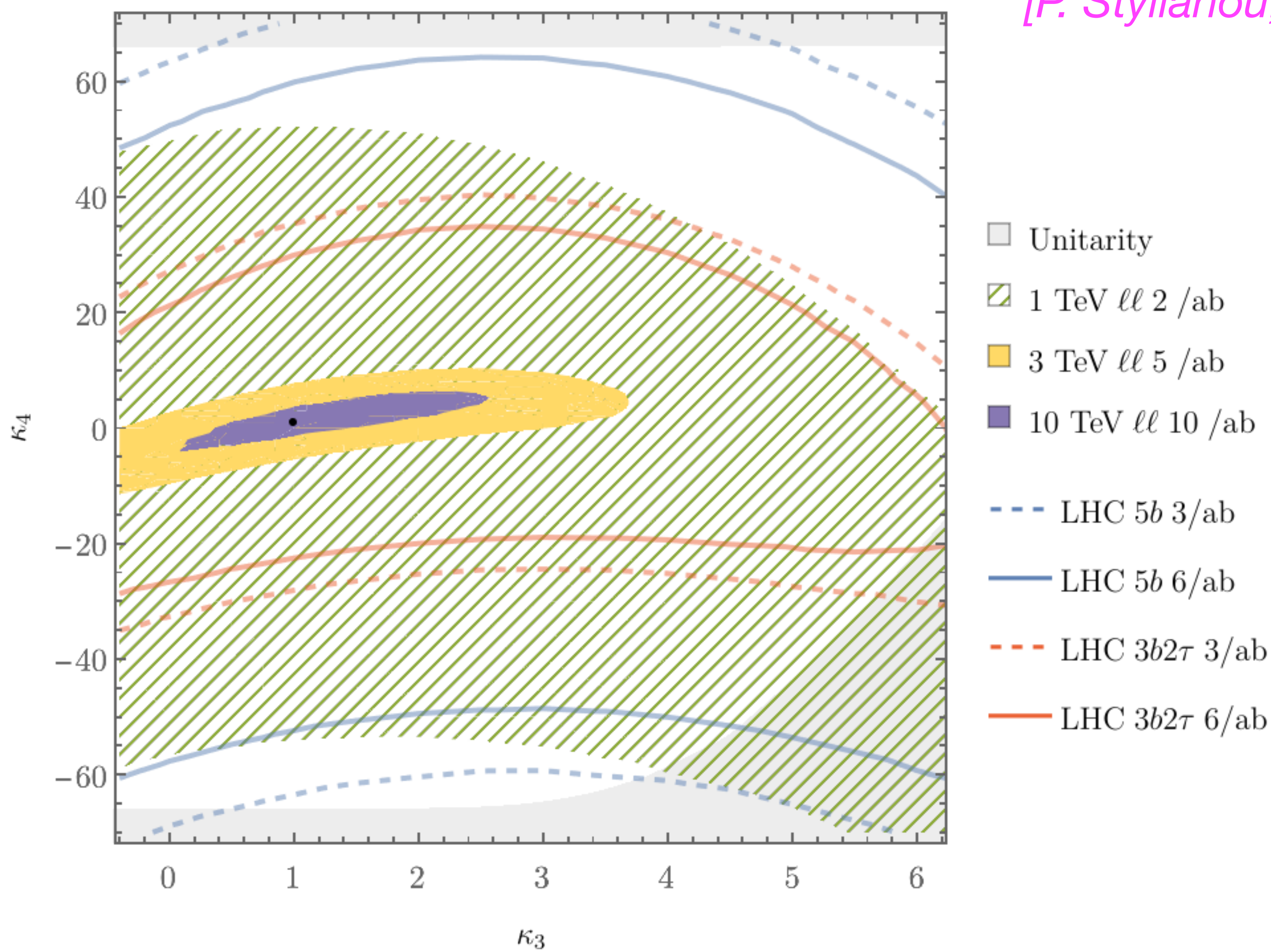
- **Assumption:** No correlations



Combination of further channels and improvements of **tagging/reconstruction** methods could enhance results further

Triple Higgs production: HL-LHC vs. lepton colliders

[P. Stylianou, G. W. ’24]



HL-LHC is competitive to 1 TeV lepton collider; higher-energetic lepton colliders have better sensitivity

Conclusions

Very profound open questions about the underlying physics of electroweak symmetry breaking, vacuum stability and the form of the Higgs potential, dark matter, observed patterns of flavour, asymmetry between matter and anti-matter in the Universe, …

Future facilities (accelerator-based and non-accelerator-based) will be able to address many of these questions and guarantee a significant gain in our understanding: scientific progress is achieved by ruling out possibilities

One possibility among the next ones to be ruled out may be the Standard Model of particle physics!

Backup

Possible relations of the Higgs and the dark sector

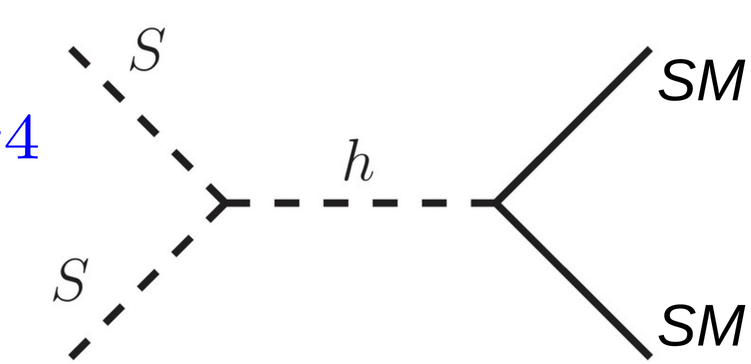
Higgs decays into dark matter particles would give rise to a ``missing energy” signature and give rise to an ``invisible” decay mode

The Higgs boson(s) could also act as a ``mediator” between the visible and the dark sector

The Higgs sector as a ``portal” to the dark sector:

- $|\Phi|^2$ is a gauge singlet → Higgs field provides a perfect way to write a **portal term** in the Lagrangian, *[J. Braathen ’24]*
  e.g. simplest example = add to SM a singlet S, charged under a global Z_2 symmetry to stabilise DM

$$\mathcal{L}_{\mathbb{Z}_2\mathrm{SSM}} = \mathcal{L}_{\mathrm{SM}} - \lambda_{\mathrm{portal}} S^2 |\Phi|^2 - \lambda_{\mathrm{dark}} S^4$$



$\lambda_{\mathrm{portal}}$: *controls DM relic density & detection*

- Plethora of models: inert singlets, doublets, triplets; Next-to-Two-Higgs-Doublet Model (N2HDM), S2HDM, etc.

QCD axion

[R. Catena '24]

- The QCD Axion is the pseudo-Nambu Goldstone boson associated with a $U_{\mathrm{PQ}}(1)$ symmetry that is spontaneously broken at f_a, and explicitly broken at T_{QCD}

- Being a CP-odd scalar, the axion contributes to the QCD Lagrangian via the term

$$\mathscr{L}_{aGG} = -\frac{\alpha_s}{8\pi}\left(\frac{a}{f_a} + \bar{\theta}\right) G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}$$

where $\bar{\theta} = \theta_{\mathrm{QCD}} + N_f\theta_Y$

- While a evolves towards the minimum of its QCD-induced potential, $a/f_a + \bar{\theta}$ goes to zero, and CP is thus preserved in the strong sector of the Standard Model

Strongly first-order EWPT in the 2HDM

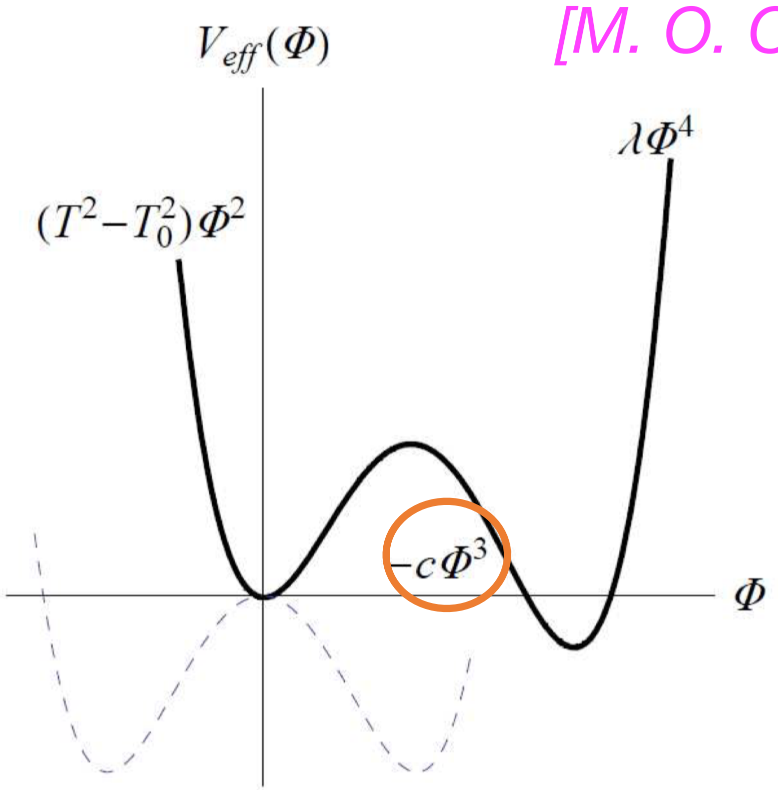
Barrier is related to a cubic term in the effective potential

Arises from higher-order contributions and thermal corrections to the potential, in particular:

$$-\frac{T}{12\pi}\left[\mu_S^2 + \lambda_{HS} h^2 + \Pi_S\right]^{3/2}$$

⇒ For sizeable quartic couplings an effective cubic term in the Higgs potential is generated

[M. O. Olea '23]



⇒ Yields mass splitting between the BSM Higgs bosons and sizeable corrections to the trilinear Higgs coupling

Where should experiment and theory meet?

- Properties of h125:
  The comparison between experiment and theory is carried out at the level of signal strengths, STXS, fiducial cross sections, … , and to a lesser extent for $\varkappa$ parameters (signal strength modifiers; see example of $\varkappa_\lambda$ below) and coefficients of EFT operators

  Public tools for confronting the experimental results with model predictions: *HiggsSignals* (signal strengths, STXS), *Lilith* (signal strengths), *HEPfit* (signal strengths), …

  New versions: *HiggsTools* *[H. Bahl et al. '22]*

- Limits from the searches for additional Higgs bosons:
  Public tools for reinterpretation / recasting of experimental results:
  HiggsBounds (limits on σ x BR, full likelihood information incorporated where provided by exp. collaborations)
  Recasting tools:
  MadAnalysis 5, *Rivet*, *ColliderBit*, *RECAST* (ATLAS-internal), …

Vacuum stability of extended Higgs sectors (T = 0)

Extended Higgs sectors with additional minima of the scalar potential at the weak scale that may be deeper than the EW vacuum

⇒ Tunneling from EW vacuum to deeper vacua possible depending on the ``bounce action” B (stationary point of the euclidian action) for the tunnelling process

⇒ EW vacuum can be short-lived, metastable or stable

Decay rate per spatial volume: $$\frac{\Gamma}{V_S} = K e^{-B}$$

``Most dangerous minimum”: highest tunnelling rate from EW vacuum

Constraints from vacuum stability at T = 0 can be combined with the ones from the thermal evolution of the Universe (see below)

``$\varkappa$ framework" and EFT approach for coupling analyses

Simplified framework for coupling analyses: deviations from SM parametrised by ``scale factors" $\varkappa_i$, where $\varkappa_i \equiv g_{Hii}/g^{SM,\,(0)}_{Hii}$

Assumptions inherent in the $\varkappa$ framework: signal corresponds to only one state, no overlapping resonances, etc., zero-width approximation, only modifications of coupling strengths (absolute values of the couplings) are considered
$\Rightarrow$ Assume that the observed state is a CP-even scalar

Theoretical assumptions in determination of the $\varkappa_i$:
$\varkappa_V \leqq 1$, no invisible / undetectable decay modes, …

EFT: fits for Wilson coefficients of higher-dimensional operators in SMEFT Lagrangian, …

Probing the SM and extended Higgs sectors

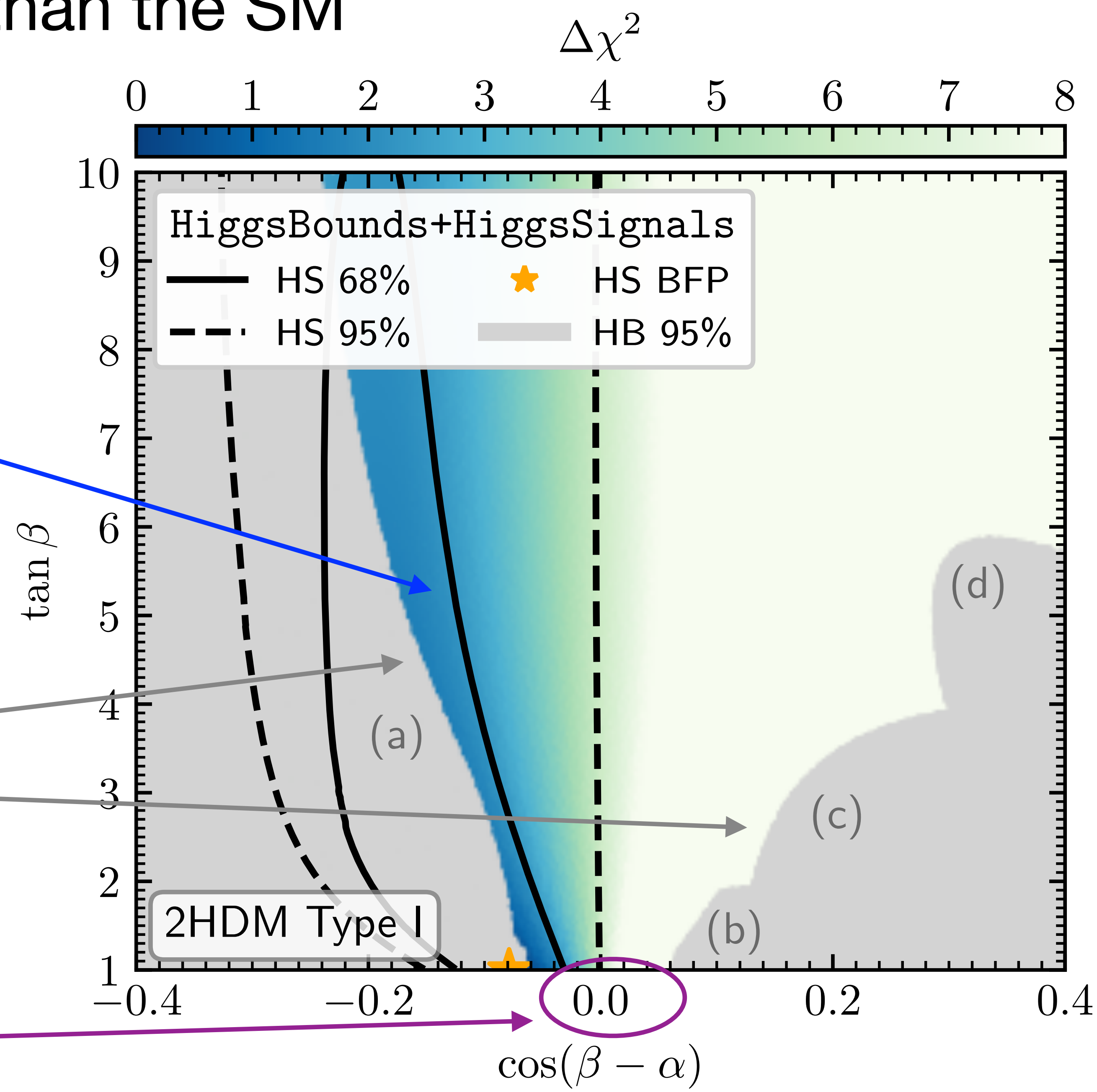
The experimental results indicate that the observed state h125 has SM-like properties, but extensions of the SM may have a higher compatibility with the data than the SM

Example: 2HDM of type I
[H. Bahl et al. '22]

Preferred region from Higgs measurements

Limits from Higgs searches

SM limit (alignment)



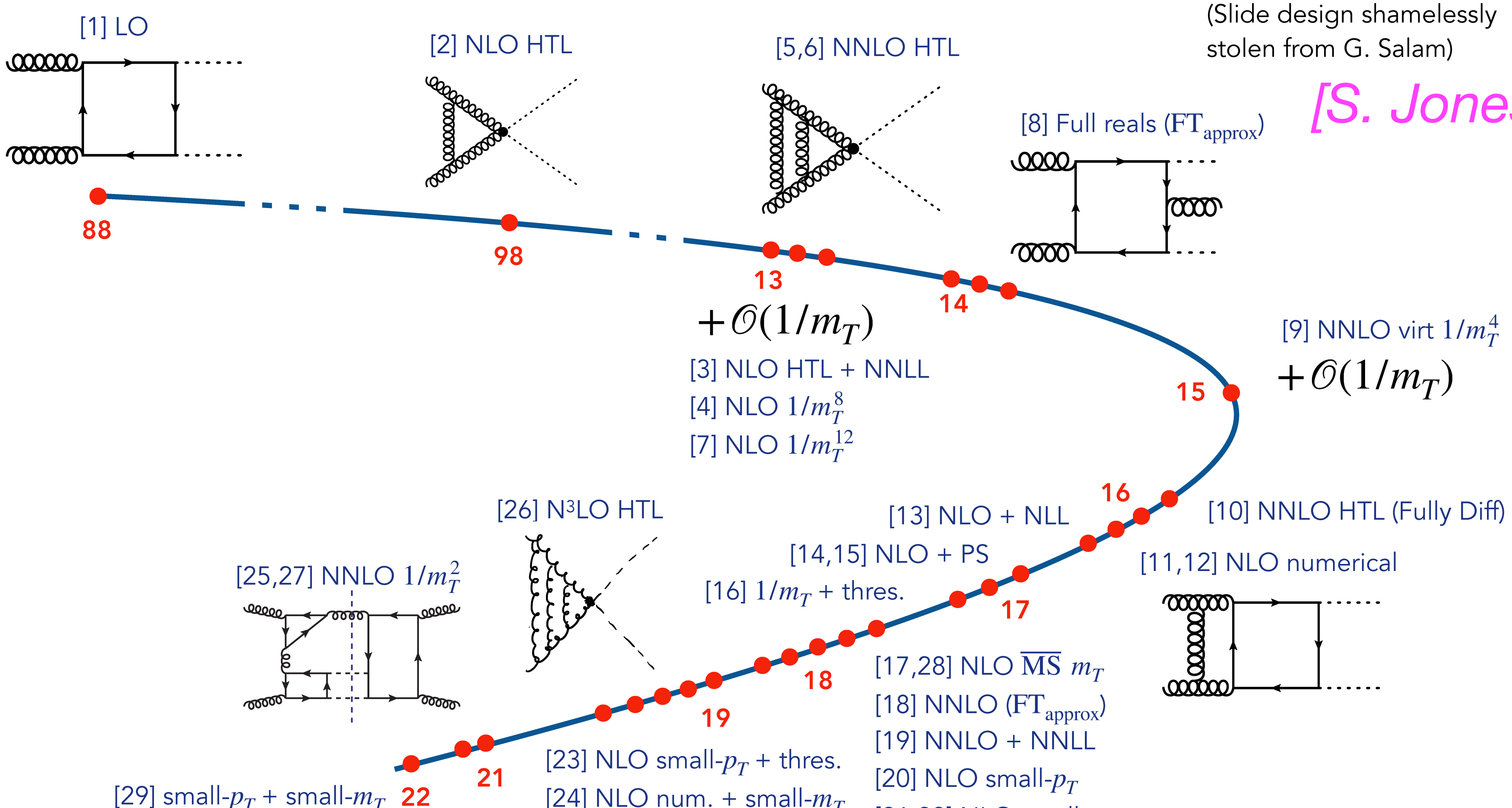
⇒Alignment limit disfavoured, slight preference for non-zero BSM contrib.

Higgs pair production: theory predictions

An approximate history (30 years in 30 seconds)

(Slide design shamelessly stolen from G. Salam)

[S. Jones, G. Salam]

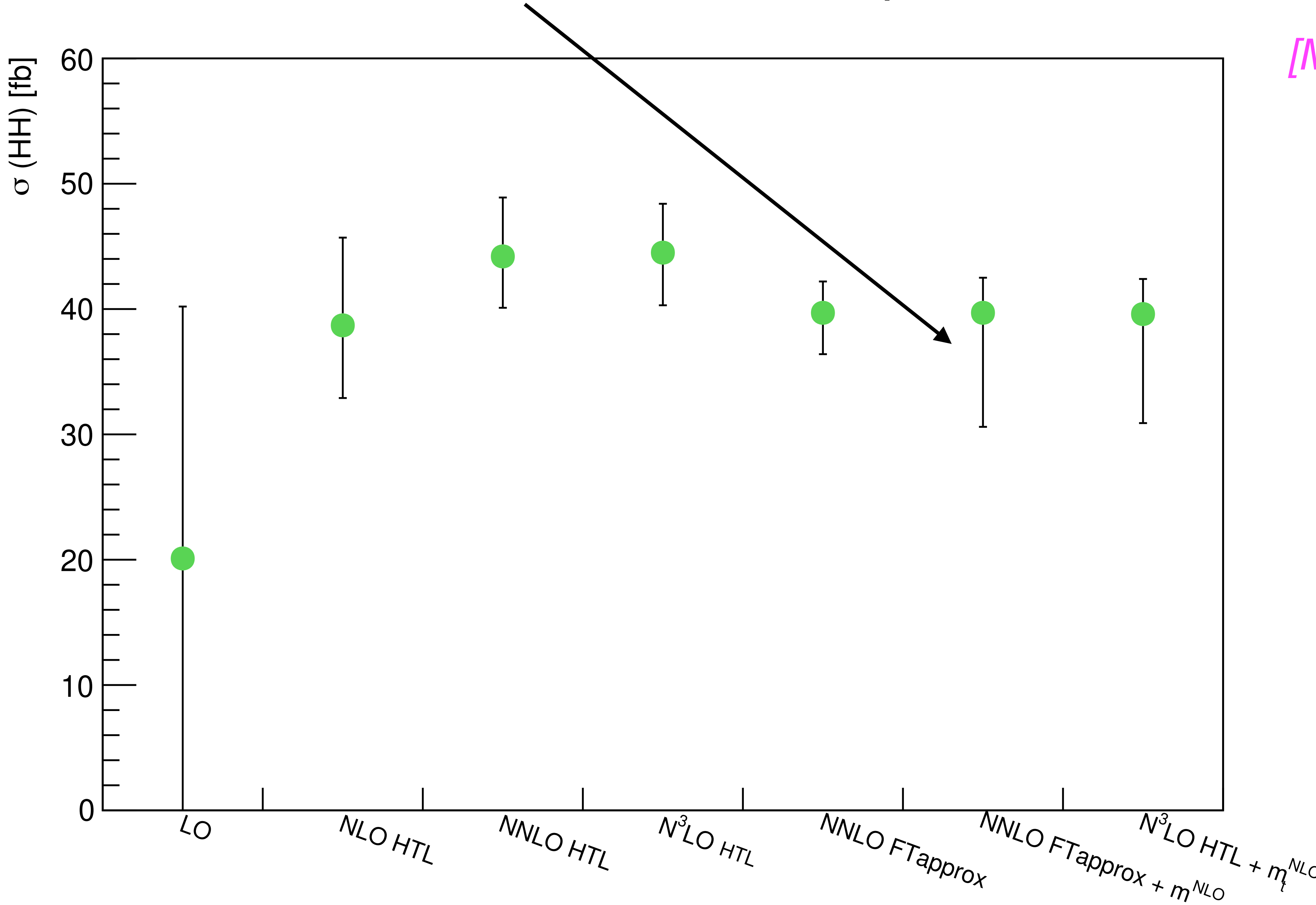


[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16; [11] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Schubert, Zirke 16; [12] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Zirke 16; [13] Ferrera, Pires 16; [14] Heinrich, SPJ, Kerner, Luisoni, Vryonidou 17; [15] SPJ, Kuttimalai 17; [16] Gröber, Maier, Rauh 17; [17] Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18; [18] Grazzini, Heinrich, SPJ, Kallweit, Kerner, Lindert, Mazzitelli 18; [19] de Florian, Mazzitelli 18; [20] Bonciani, Degrassi, Giardino, Gröber 18; [21] Davies, Mishima, Steinhauser, Wellmann 18, 18; [22] Mishima 18; [23] Gröber, Maier, Rauh 19; [24] Davies, Heinrich, SPJ, Kerner, Mishima, Steinhauser, David Wellmann 19; [25] Davies, Steinhauser 19; [26] Chen, Li, Shao, Wang 19, 19; [27] Davies, Herren, Mishima, Steinhauser 19, 21; [28] Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 21; [29] Bellafronte, Degrassi, Giardino, Gröber, Vitti 22;

Higgs pair production, prediction and uncertainties

Impact of the renormalisation-scheme dependence of the top mass:

[M. Spira '22]

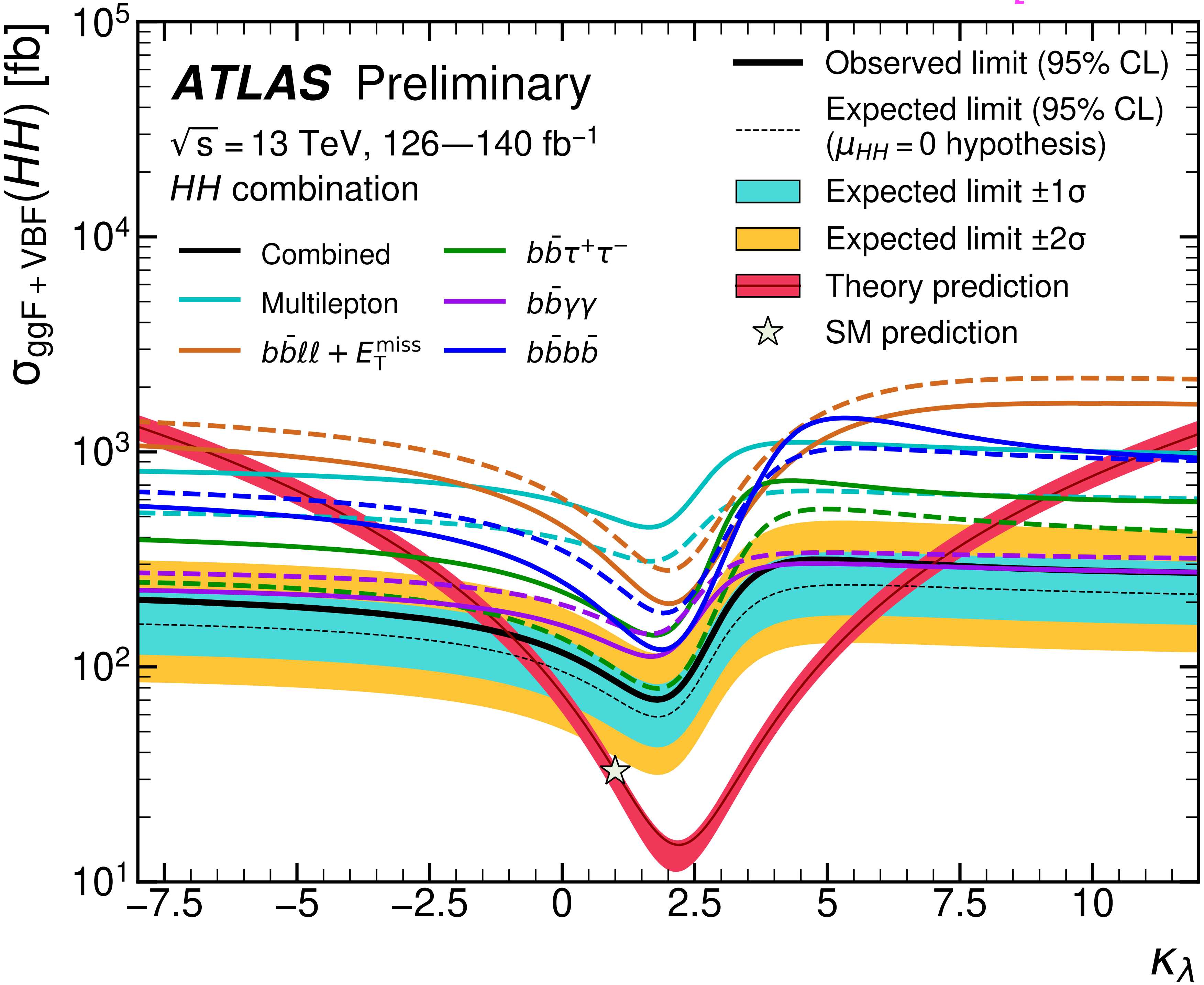


Electroweak corrections: top-Yukawa contributions

[M. Mühlleitner, J. Schlenk, M. Spira '22] [J. Davies et al. '22]

New ATLAS combination

[ATLAS Collaboration ’24]

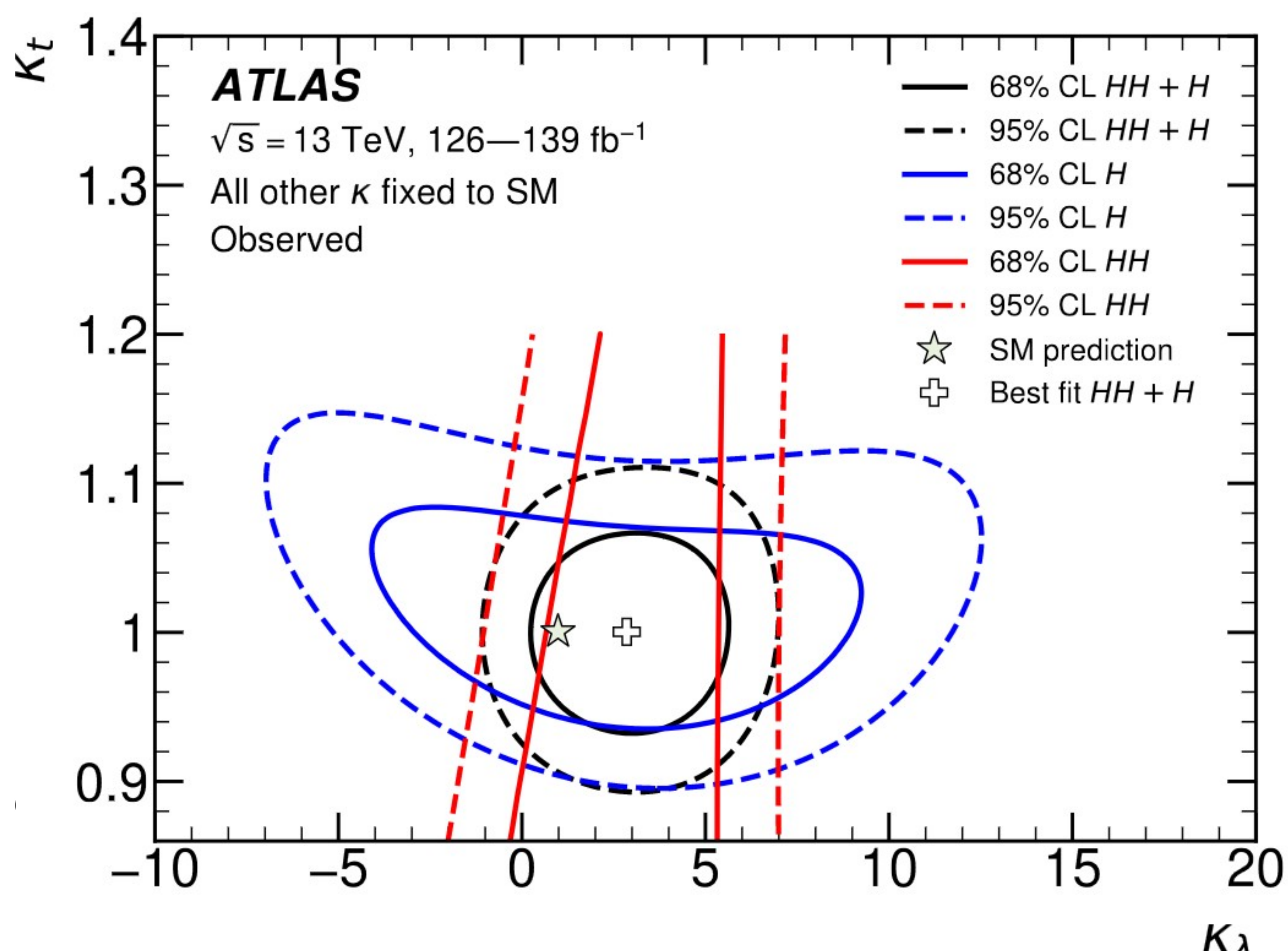


ATLAS: $-1.2 < \kappa_\lambda < 7.2$ at 95% C.L. ($-1.6 < \kappa_\lambda < 7.2$ expected)

Experimental constraints on $\varkappa_\lambda$

[ATLAS Collaboration '22]

Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.5$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.3 < \kappa_\lambda < 6.1$	$-2.1 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

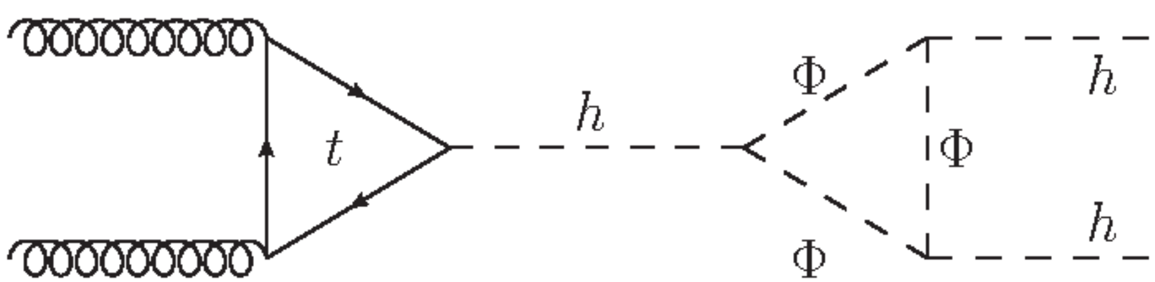


Check of applicability of the experimental limit on $\varkappa_\lambda$

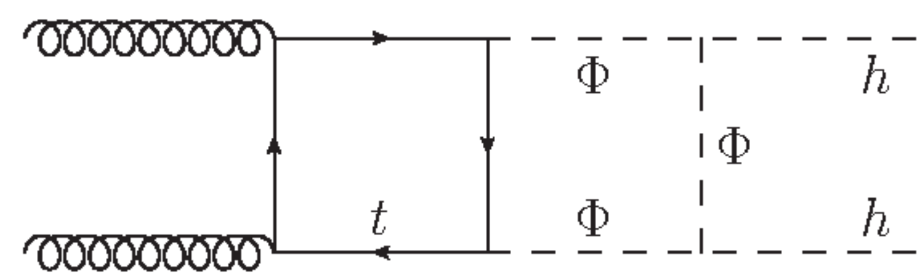
Alignment limit: h has SM-like tree-level couplings

Resonant contribution to Higgs pair production with H or A in the s channel is absent in the alignment limit

The dominant new-physics contributions enter via trilinear coupling



$\propto \mathcal{O}(y_t g^3_{hh\Phi\Phi})$ ***included***



$\propto \mathcal{O}(y_t^2 g^2_{hh\Phi\Phi})$ *not included*

⇒The leading effects in $g_{hh\phi\phi}$ to the Higgs pair production process are correctly incorporated at the 1- and 2-loop order via the corrections to the trilinear Higgs coupling!

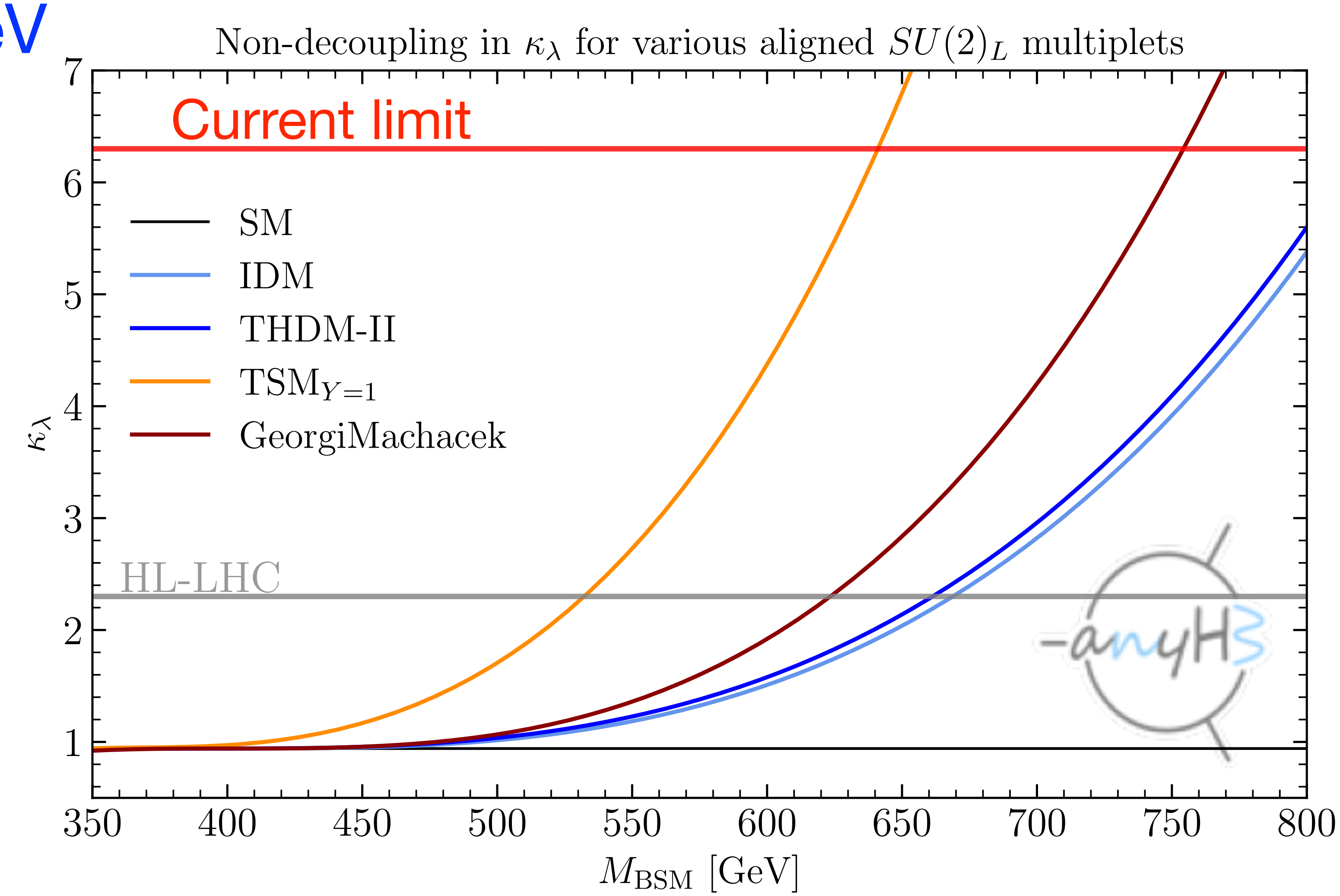
Higgs self-couplings in extended Higgs sectors

Effect of splitting between BSM Higgs bosons:

Very large corrections to the Higgs self-couplings, while all couplings of h_{125} to gauge bosons and fermions are SM-like (tree-level couplings agree with the SM in the alignment limit)

[H. Bahl, J. Braathen, M. Gabelmann, G. W. '23]

M_L = 400 GeV



[see parallel session talk by J. Braathen]

Single-Higgs processes: λ enters at loop level

[E. Petit '19]

How to measure deviations of λ_3

- The Higgs self-coupling can be assessed using di-Higgs production and single-Higgs production
- The sensitivity of the various future colliders can be obtained using four different methods:

	di-Higgs	single-H
exclusive	**1. di-H, excl.** • Use of $\sigma(HH)$ • only deformation of $\kappa\lambda$	**3. single-H, excl.** • single Higgs processes at higher order • only deformation of $\kappa\lambda$
global	**2. di-H, glob.** • Use of $\sigma(HH)$ • deformation of $\kappa\lambda$ + of the single-H couplings (a) do not consider the effects at higher order of $\kappa\lambda$ to single H production and decays (b) these higher order effects are included	**4. single-H, glob.** • single Higgs processes at higher order • deformation of $\kappa\lambda$ + of the single Higgs couplings

Note: this is based on the assumption that there is a large shift in λ, but no change anywhere else!

Single-Higgs processes: λ enters at loop level

[B. Heinemann ’19]

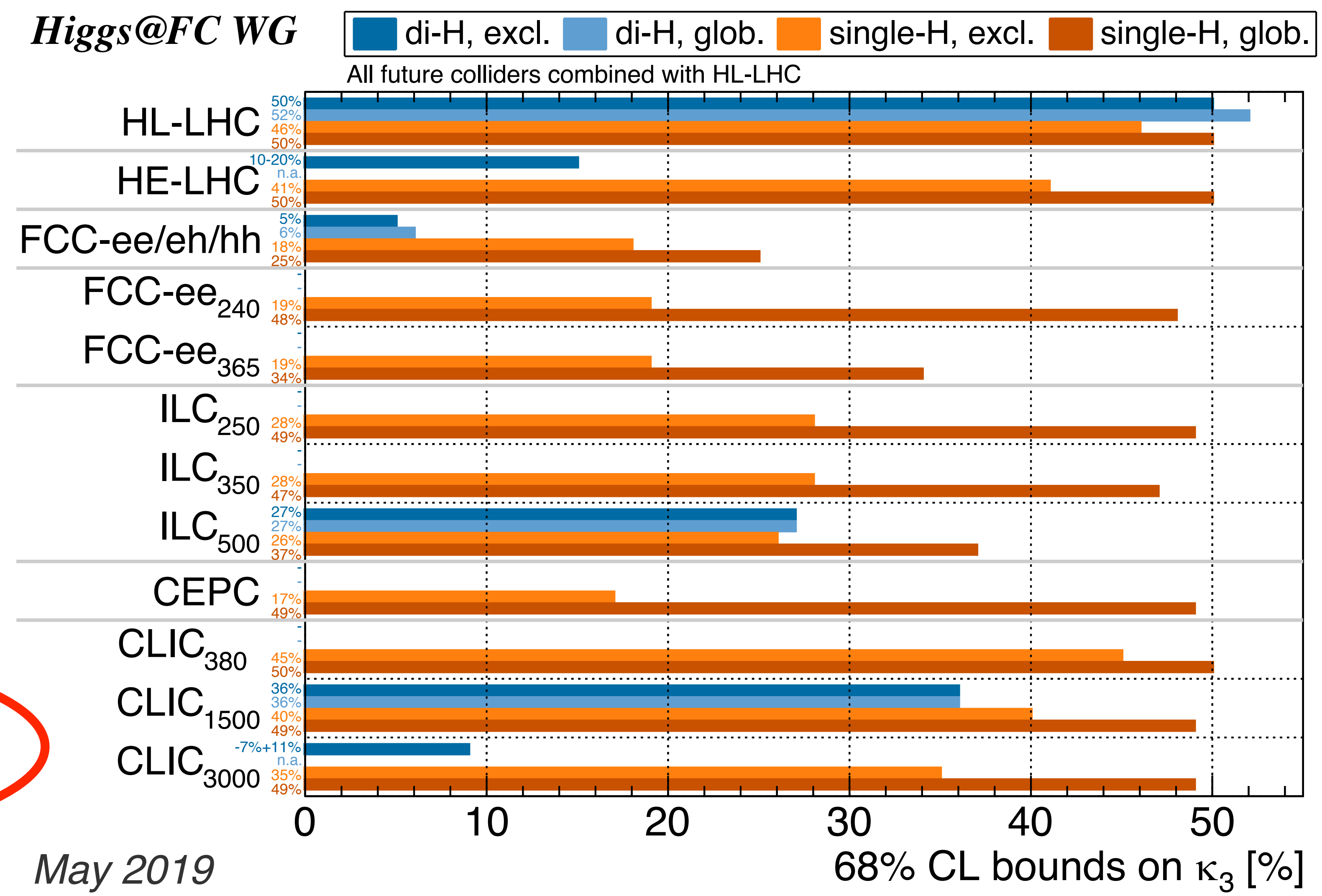
Sensitivity to λ: via single-H and di-H production

Di-Higgs:

- HL-LHC: ~50% or better?
- Improved by HE-LHC (~15%), ILC_{500} (~27%), $CLIC_{1500}$ (~36%)
- Precisely by $CLIC_{3000}$ (~9%), FCC-hh (~5%),
- Robust w.r.t other operators

Single-Higgs:

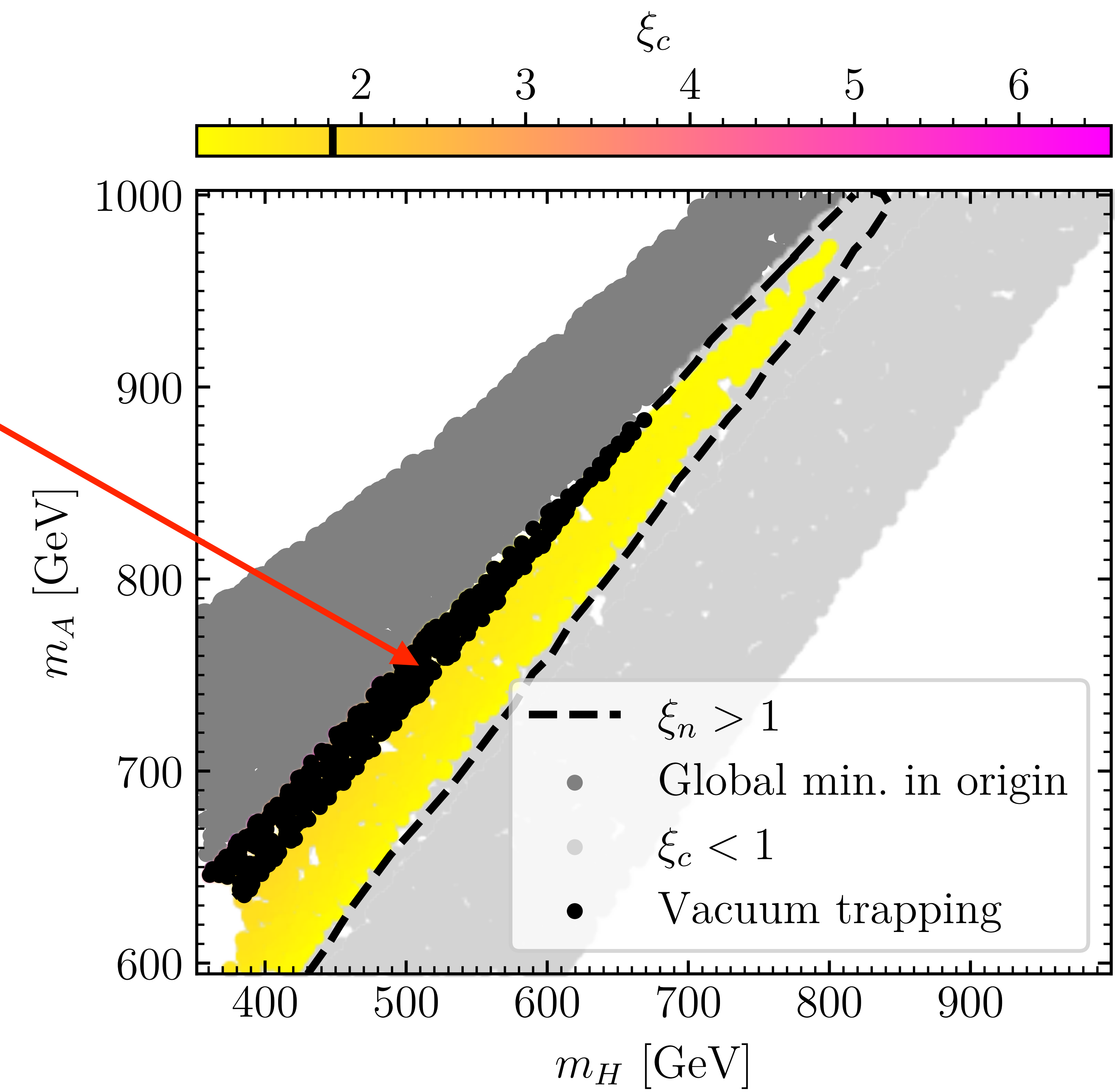
- **Global** analysis: FCC-ee365 and ILC500 sensitive to ~35% when combined with HL-LHC
  - ~21% if FCC-ee has 4 detectors
- **Exclusive** analysis: too sensitive to other new physics to draw conclusion



2HDM of type II: region of strong first-order EWPT

[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. '22]

Constraints from "vacuum trapping": the universe may remain "trapped" in a symmetry-conserving vacuum at the origin, because the conditions for a transition into the deeper EW-breaking minimum are not fulfilled

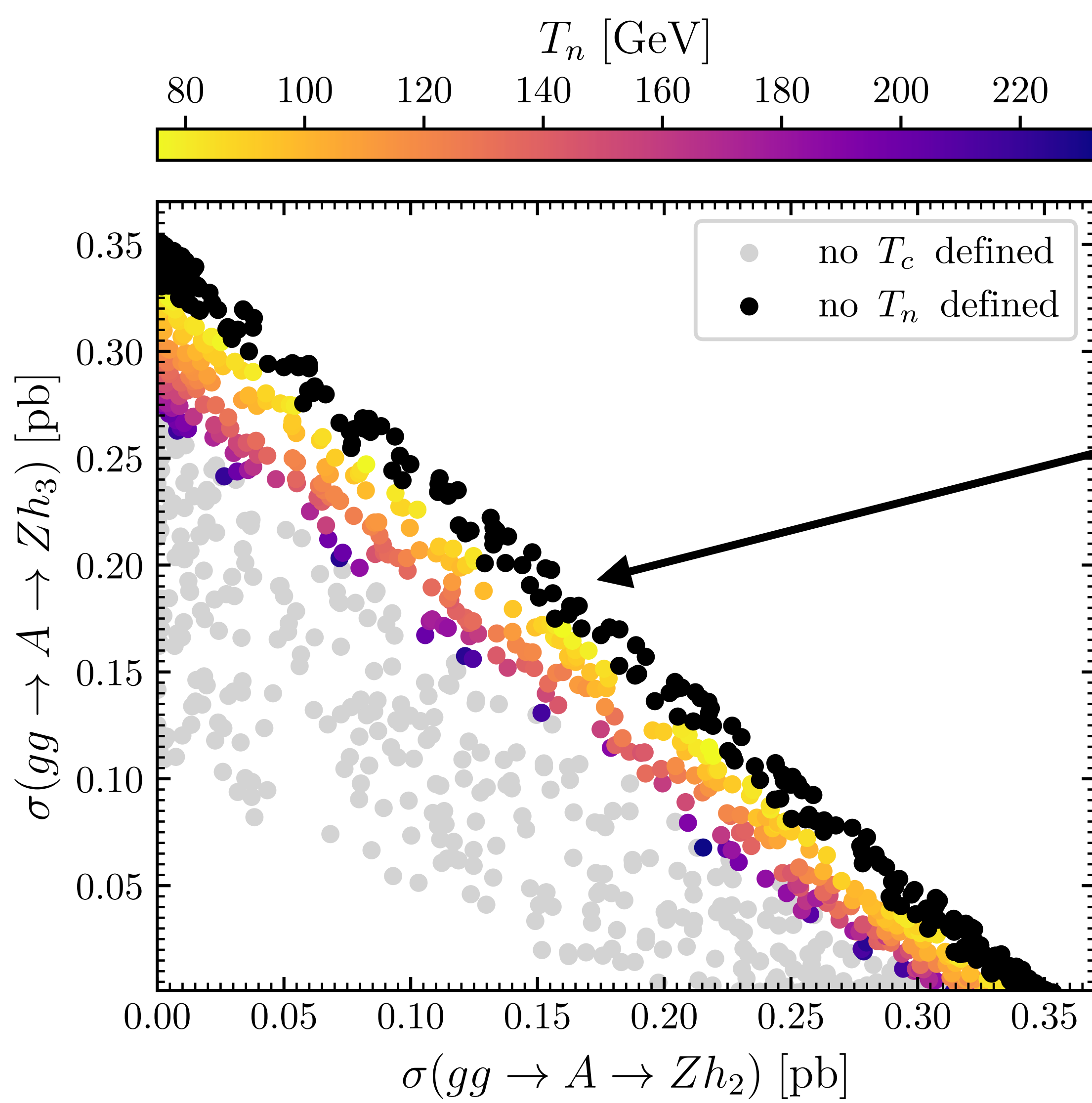


N2HDM (two doublets + real singlet) example

``Smoking gun" collider signatures: A → Z h_2, A → Z h_3

Nucleation temperature for the first-order EWPT, N2HDM scan:

[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. '21]

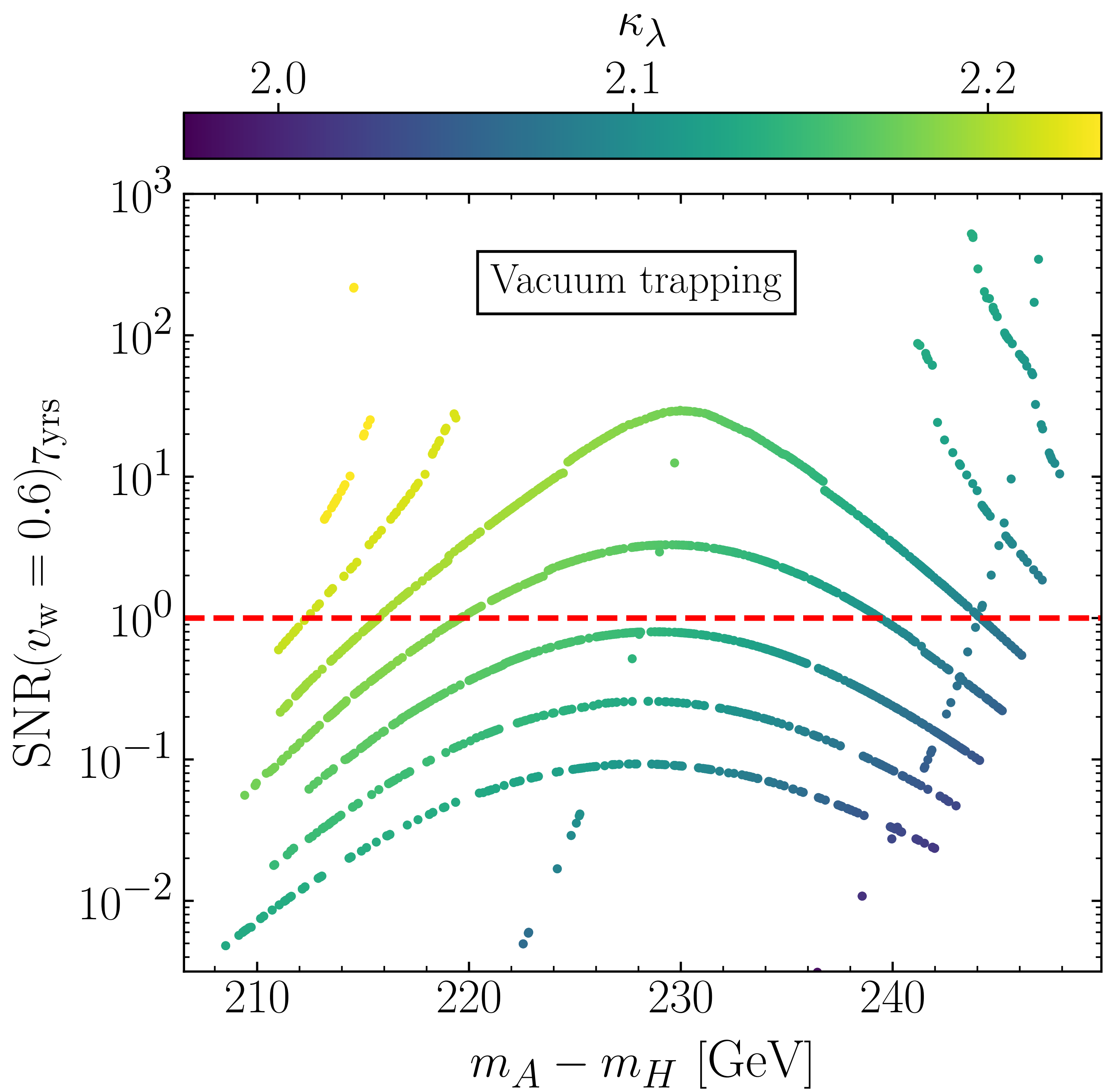


No first-order EWPT: universe is trapped in a ``false" vacuum

⇒ Lower nucleation temperatures, i.e. stronger first-order EWPTs, are correlated with larger signal rates at the LHC!

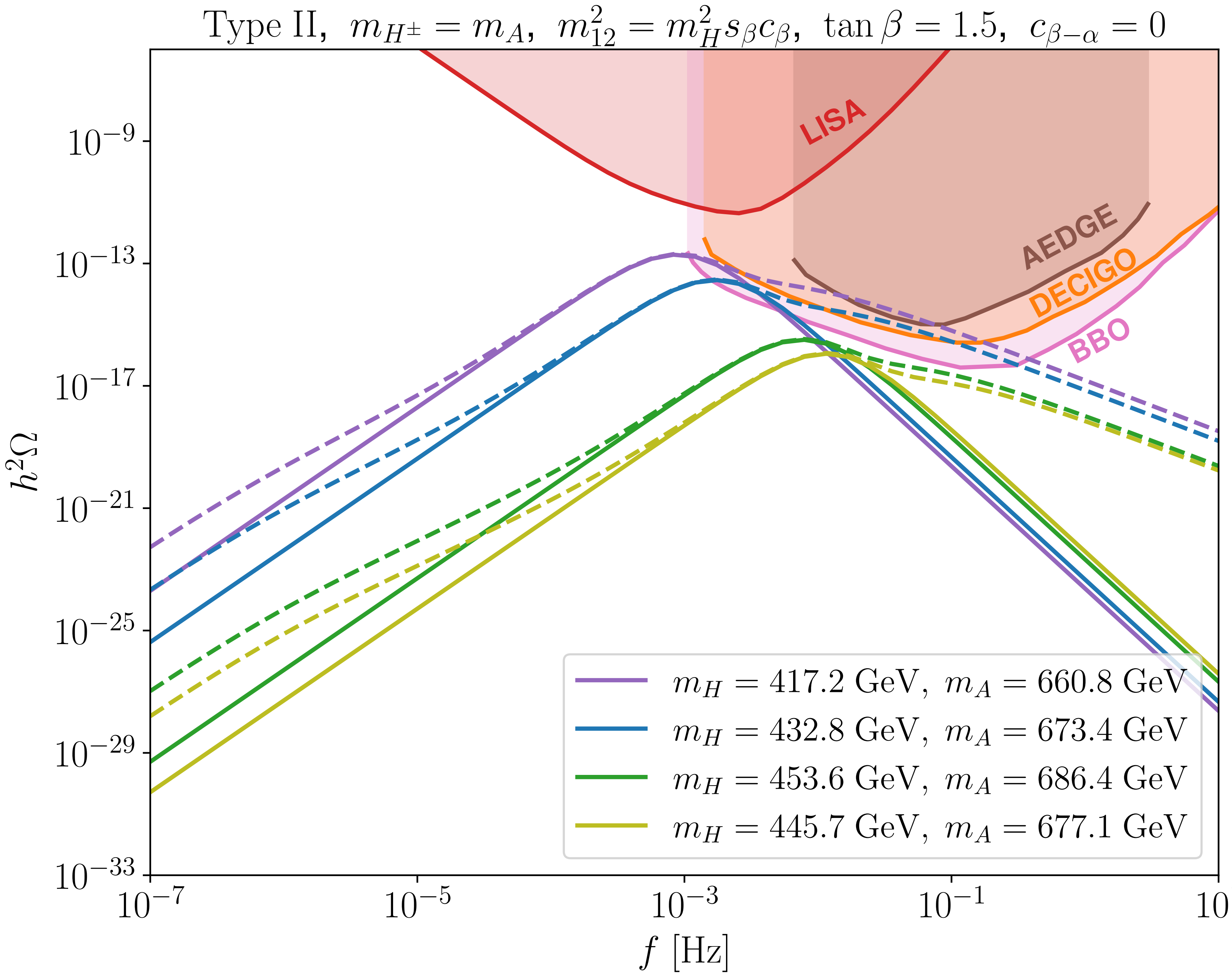
Correlation of κ_λ with the signal-to-noise ratio (SNR) of a gravitational wave signal at LISA

[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. '22]



⇒Region with potentially detectable gravitational wave signal: significant enhancement of κ_λ and non-vanishing mass splitting

GW spectra of scenarios fitting the excess

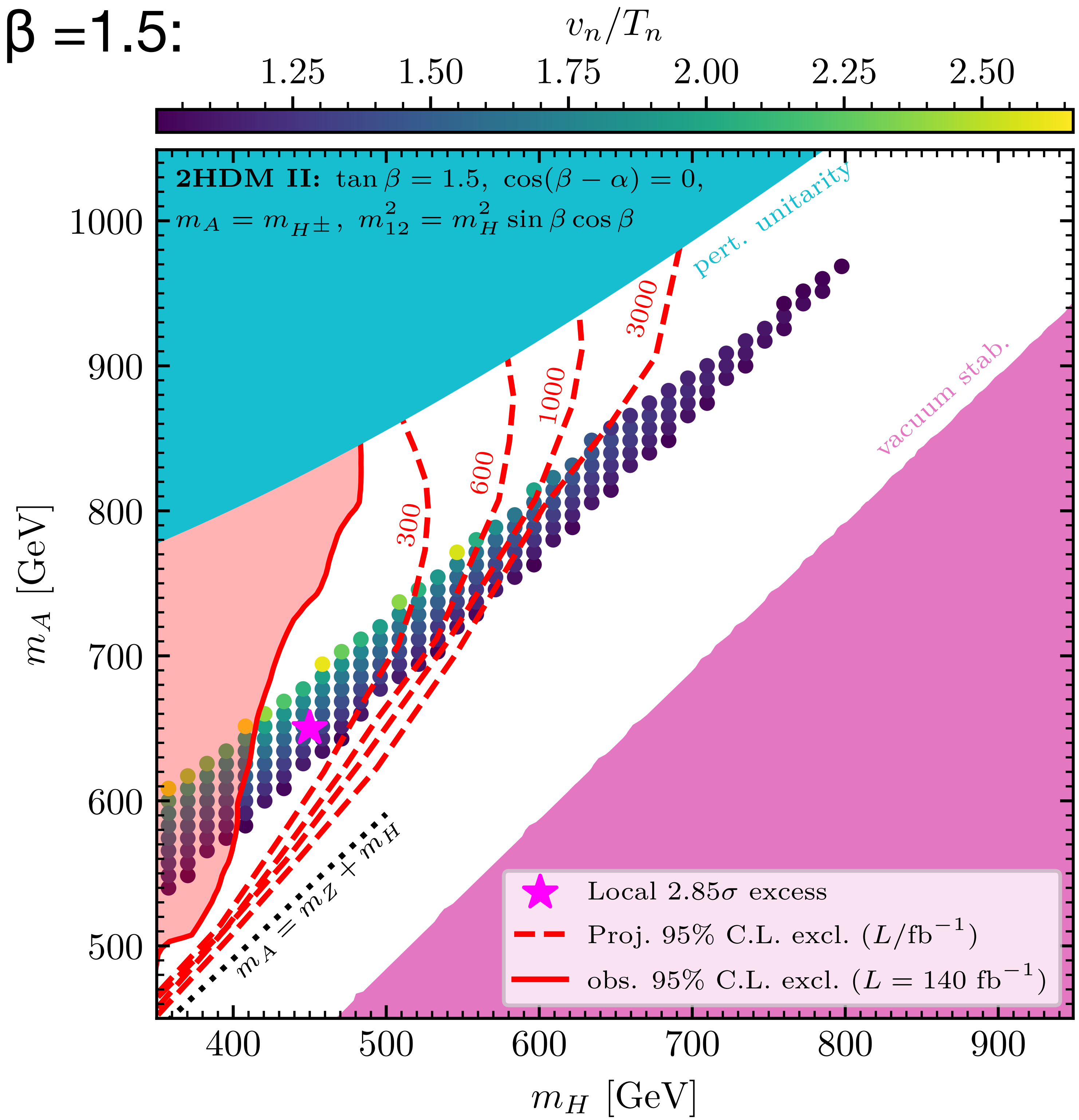


[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, K. Radchenko, G. W. '23]

⇒ Prospects for GW detection depend very sensitively on the precise details of the mass spectrum of the additional Higgs bosons

Projection for future sensitivity based on ATLAS result

2HDM, tanβ =1.5:



[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, K. Radchenko, G. W. '23]

⇒Good agreement with projection based on expected CMS limit

Further "smoking gun" signature

The parameter region that potentially gives rise to a strong first-order EWPT can also be probed via the search

$$H^{\pm} \to W^{\pm} H \to \ell^{\pm} \nu t\bar{t}$$

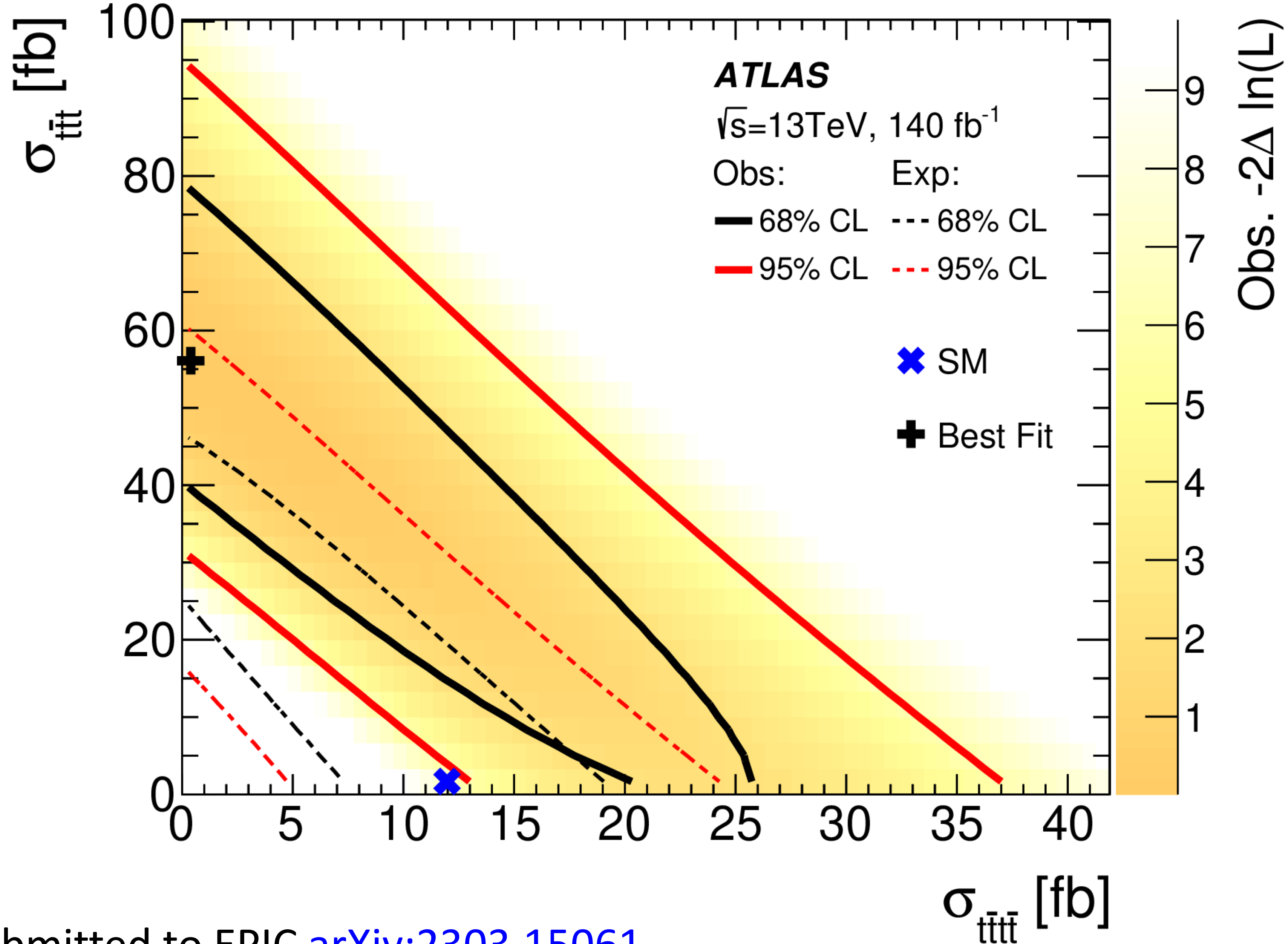
For the production of the charged Higgs together with *t b* this yields a 4-top like or 3-top like final state

Results for the 4-top final state exist from ATLAS and CMS (and for 3-top vs. 4-top from ATLAS), but so far no dedicated experimental analysis for the charged Higgs channel has been performed!

ATLAS: 3-top vs. 4-top final states

ATLAS: three tops?

[ATLAS Collaboration '23]



Submitted to EPJC arXiv:2303.15061

freyablekman FH physics discussion